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BOOK OF PROCEEDINGS



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Foreword

Dear colleagues, esteemed authors, participants, partners, and friends of the Conference,

It is with great pleasure that I present the Book of Proceedings of the 10th Anniversary International Professional and Scientific Conference Occupational Safety and Health, taking place in Zadar, Croatia, from 16 to 19 September 2026. This year's edition marks an important milestone, as it commemorates twenty years since the inaugural Conference was held in 2006.

Since its beginnings, the Conference has continued to grow, bringing together an increasing number of participants from the scientific and professional communities. Over the past two decades, it has developed into a recognised forum where science and professional practice converge, knowledge and experience are exchanged, and Croatian and international experts in occupational safety and health establish valuable connections. Its continuity and sustained development confirm that occupational safety and health are not merely scientific and professional concerns, but also a fundamental responsibility of society as a whole.

This anniversary edition brings together participants from Croatia and six other countries: Portugal, Bosnia and Herzegovina, Slovenia, Hungary, Serbia, and North Macedonia. The Conference's international recognition and quality are further enhanced by the cooperation of Karlovac University of Applied Sciences with its partner institutions: the Polytechnic Institute of Beja in Portugal, the University of Niš Faculty of Occupational Safety in Serbia, the International Slavic University "G. R. Derzhavin" in North Macedonia, the University of Novo mesto Faculty of Mechanical Engineering in Slovenia, and the University of Rijeka Faculty of Health Studies in Croatia.

This Book of Proceedings contains 123 accepted scientific and professional papers, organised into eight thematic sections: Occupational Safety, Occupational Health, Technical and Technological Factors, Ergonomics, Environmental Protection, Fire and Explosion Protection, Social and Humanistic Aspects, and Multidisciplinary Aspects. The diversity of the topics, research approaches, and professional experiences represented in this volume reflects the distinctly interdisciplinary nature of occupational safety and health.

The tenth edition of the Conference provides an opportunity to reflect on the path we have travelled, but above all to look towards the future. The contemporary world of work is changing rapidly under the influence of emerging technologies, automation, artificial intelligence, climate change, demographic trends, and new organisational models. While these developments offer numerous opportunities, they also create new risks and present professionals with increasingly complex challenges. For this reason, the exchange of scientific knowledge, professional experience, and examples of good practice is of exceptional importance.

Since its inception, one of the Conference's particular strengths has been its ability to connect science and professional practice. Plenary lectures, oral presentations of scientific and professional papers, poster sessions, and thematic round-table discussions provide a forum for open dialogue on current challenges and facilitate the exchange of ideas among different professions and institutions. This year's round tables, entitled Digital Footprint and Mental Health in the Business Environment and Changes in Occupational Safety Regulations – Direction of Development and Expectations in Implementation, further demonstrate the Conference's focus on current issues and the future development of the profession.

The papers collected in this Book of Proceedings contribute to a better understanding of both existing and emerging risks, as well as to the development of effective preventive measures and contemporary solutions. I believe that this volume will serve as a valuable source of knowledge for researchers, academics, practitioners, policymakers, and students, while also encouraging new research, partnerships, and the application of the presented findings in real working environments.

On behalf of Karlovac University of Applied Sciences, I would like to thank all co-organisers, partner institutions, and patrons who have supported the development of the Conference over the years. I extend my sincere gratitude to the authors for their trust and valuable contributions, to the reviewers for their expertise and diligence, to the invited speakers and all participants, and to the members of the Programme, Scientific, and Organising Committees. Their commitment, knowledge, and joint efforts have enabled the Conference to reach its landmark tenth edition.

The tenth Conference is not merely an occasion to celebrate an important anniversary. It represents a confirmation of continuity, professional responsibility, and our shared commitment to the goal that has united us for the past twenty years: creating working environments that safeguard the health, safety, and dignity of every individual.

I wish all authors, participants, and readers of this Book of Proceedings successful work, inspiring discussions, valuable new professional connections, and every success in their future scientific and professional endeavours.

Dean of the Karlovac University of Applied Sciences

Ivan Štedul



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Review article

FROM DIGITALIZATION AND CYBERNATION TO COGNITIZATION: A HUMAN-CENTRIC APPROACH TO NEXT-GENERATION OCCUPATIONAL SAFETY IN CYBER-PHYSICAL PRODUCTION SYSTEMS

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Abstract: *The ongoing digital transformation of manufacturing has profoundly reshaped the way occupational safety is understood and managed. Traditional, reactive approaches are increasingly being replaced by intelligent, data-driven systems capable of monitoring and responding to risks in real time. Within the framework of Industry 4.0, the integration of digitalization and cybernation has led to the development of Cyber-Physical Production Systems (CPPS), which connect physical processes with digital control and communication infrastructures. However, the growing complexity of these systems, together with the evolving role of the human operator, calls for a further step towards cognitization and human-centric design.*

This paper proposes a conceptual pathway from CPPS to Cognitive Cyber-Physical Production Systems (C-CPPS) as a foundation for the emerging paradigm of Safety 5.0. By incorporating artificial intelligence and cognitive technologies, the proposed framework is designed to support predictive risk assessment, early anomaly detection, and adaptive decision-making. Particular attention is given to the transformation of the human role—from a system operator to an active cognitive partner within integrated socio-cyber-physical environments.

The paper suggests that combining cognitive technologies with human-centric principles can enhance occupational safety, system resilience, and overall operational performance. In doing so, it offers a coherent perspective on the future of safety in advanced manufacturing systems aligned with the vision of Industry 5.0.

Keywords: *Industry 5.0; Safety 5.0; Cyber-Physical Production Systems (CPPS); Cognitive Cyber-Physical Production Systems (C-CPPS); Human Digital Twin (HDT); Cognitive Digital Twins (CDT); Artificial Intelligence (AI); Safety Intelligence (SI); Cognitive Cyber-Physical Safety Systems (C-CPSS)*

1. INTRODUCTION

Manufacturing systems are undergoing a profound transformation driven by digital technologies, artificial intelligence (AI), cyber-physical systems (CPS), and advanced communication infrastructures. Within the Industry 4.0 paradigm, these technologies have enabled increasingly connected, data-driven, and autonomous production environments, leading to the emergence of Cyber-Physical Production Systems (CPPS) as a key technological foundation of smart manufacturing [1–9].

While these developments have significantly improved productivity, flexibility, and operational efficiency, they have also introduced new challenges for occupational safety and health (OSH). Traditional safety approaches based on accident investigation, compliance, and corrective actions are increasingly insufficient in highly interconnected and dynamic manufacturing environments [10,11]. Modern production systems require safety approaches capable of anticipating risks, supporting proactive decision-making, and continuously adapting to changing operational conditions.

At the same time, the role of humans in manufacturing is changing. Workers increasingly act as supervisors, coordinators, and decision-makers within complex socio-technical systems rather than performing purely operational tasks [12]. This evolution is consistent with the Industry 5.0 vision, which emphasizes human-centricity, resilience, sustainability, and collaboration between human intelligence and artificial intelligence [13–16].

The transition from Industry 4.0 to Industry 5.0 reflects a broader technological evolution. While digitalization enabled information acquisition and exchange, and cybernation established close integration between physical and digital systems, future manufacturing environments require contextual understanding, learning, reasoning, and adaptive decision-making. These capabilities characterize cognitization, an emerging stage of industrial development that extends beyond connectivity and automation [17–20].

From an occupational safety perspective, cognitization creates the foundation for a new generation of intelligent safety systems capable of supporting dynamic risk assessment, early hazard detection, adaptive interventions, and human-centered decision support. Consequently, conventional CPPS may evolve into Cognitive Cyber-Physical Production Systems (C-CPPS), where human intelligence and AI operate as complementary components within integrated socio-cyber-physical environments [17–20].

Despite growing research activity in Industry 4.0, digital twins, AI, and smart manufacturing, the integration of these concepts within occupational safety management remains fragmented. In particular, the concept of Safety 5.0 lacks a coherent framework explaining the relationships among cognitization, C-CPPS, Human Digital Twins (HDT), Cognitive Digital Twins (CDT), Safety Intelligence (SI), and Human–AI collaboration [13–20].

To address this gap, this paper proposes a Human-Centric Cognitive Safety Framework that integrates C-CPPS, HDT, CDT, Safety Intelligence, and Human–AI Collaboration within a unified Safety 5.0 model. The main contributions are: (i) establishing an evolutionary pathway from digitalization and cybernation toward cognitization, (ii) defining C-CPPS as the technological realization of cognitization, (iii) formalizing the concept of SI, and (iv) proposing a human-centric Safety 5.0 framework for future socio-cyber-physical manufacturing environments.

2. EVOLUTION OF MANUFACTURING SYSTEMS: FROM MECHANIZATION TO COGNITIZATION

The development of manufacturing systems can be viewed as a progressive transition from mechanization toward increasingly intelligent and human-centric production environments. Figure 1 illustrates this evolutionary pathway, highlighting the progression from Industry 1.0 to the emerging cognitization stage associated with Industry 5.0 [20].

Mechanization introduced machine-assisted production based on steam power and established the foundations of industrial manufacturing [21]. During the subsequent stages of automation, electrical power, programmable control systems, CNC technologies, and industrial robotics enabled machines to perform predefined operations with progressively reduced human intervention [1,3,22]. As illustrated in Figure 2, the role of humans gradually evolved from direct operators toward supervisors and coordinators of increasingly automated production systems [20].

The emergence of Industry 4.0 marked a transition toward digitalized manufacturing environments characterized by extensive connectivity, data acquisition, and real-time information exchange. Technologies such as IIoT, cloud computing, artificial intelligence, big data analytics, and digital twins enabled continuous monitoring, predictive analytics, and decentralized decision-making [1–9,23–29]. The technological architecture of digitalized manufacturing systems is illustrated in Figure 3.

As digitalization matured, manufacturing systems evolved toward CPPS, where physical and digital domains became tightly integrated through continuous feedback loops and real-time communication [7,8,30]. This stage, referred to in this paper as cybernation, enabled self-monitoring, adaptive control, predictive maintenance, and enhanced operational visibility. Figure 4 presents the conceptual architecture of a typical CPPS [31].

Despite these advances, current CPPS remain largely dependent on predefined models, historical data, and predictive algorithms. Although they support connectivity, monitoring, and autonomous control, they provide only limited capabilities for contextual understanding, reasoning, knowledge generation, and adaptive learning [17,18,32–34]. Furthermore, existing CPPS architectures primarily focus on technological optimization, while human operators often remain supervisors rather than active cognitive partners [12,34–39]. These limitations become particularly important in occupational safety applications, where risks frequently emerge from complex interactions among technological, organizational, and human factors [10,11,35,36].

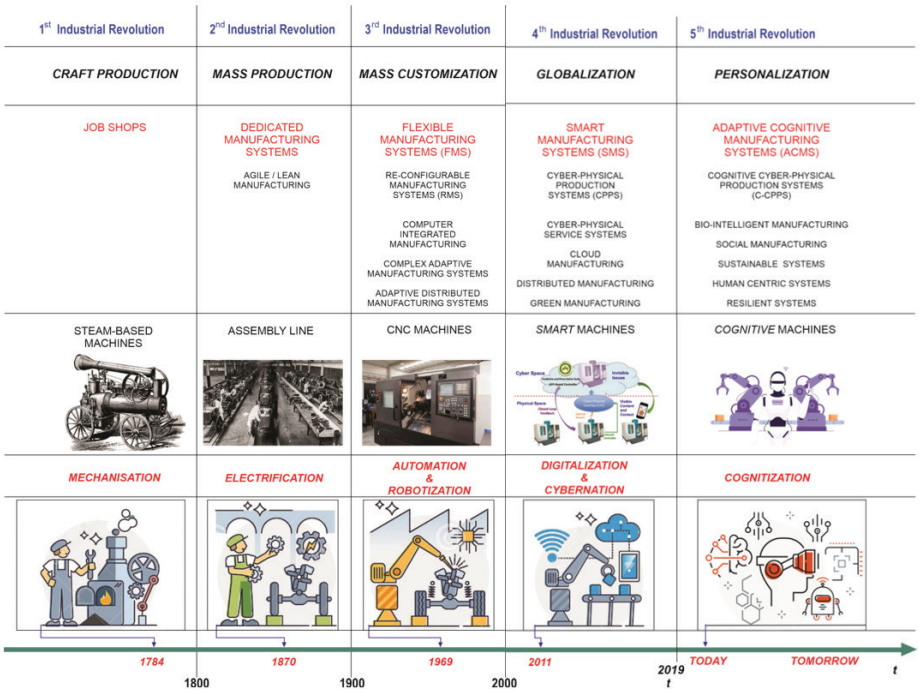


Figure 1: Evolution of Manufacturing Systems from Mechanization to C-CPPS [20]

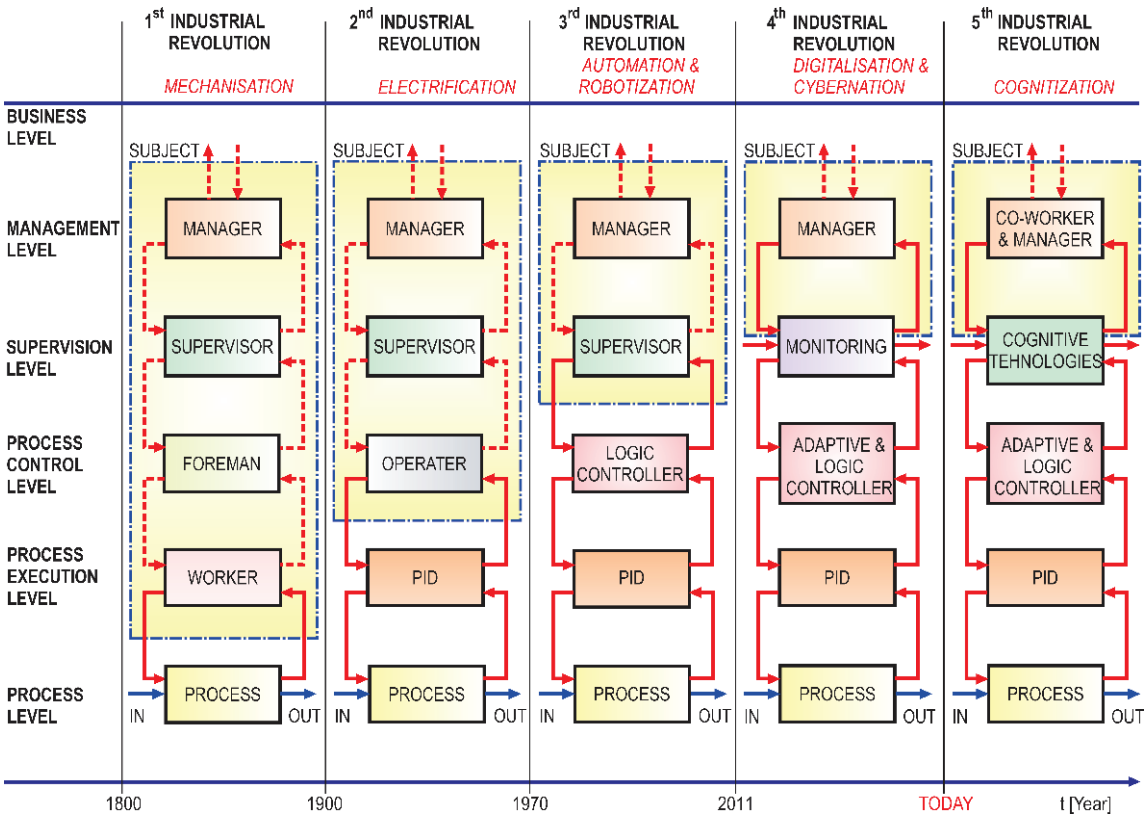


Figure 2: Evolution of the human role in manufacturing systems [20]

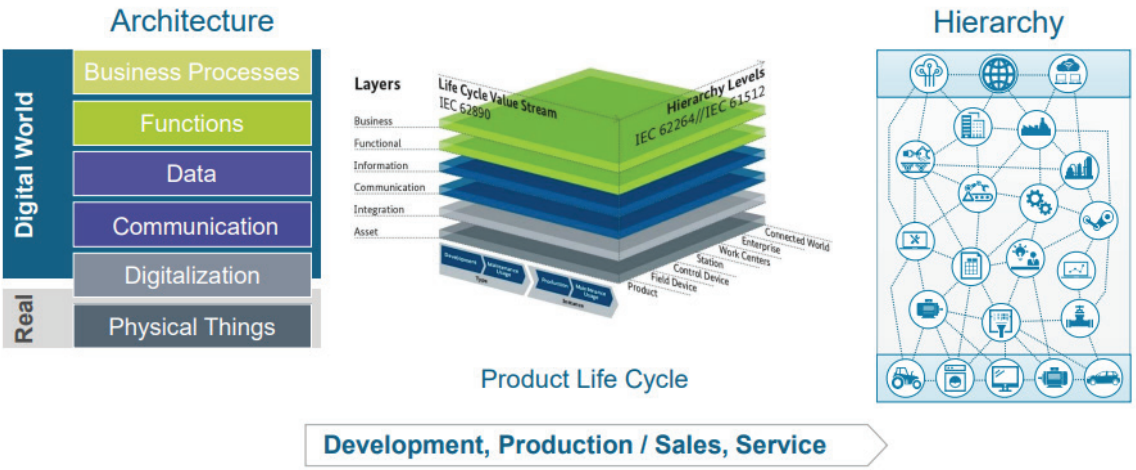


Figure 3: Technological Architecture of Industry 4.0 and Digitalized Manufacturing Systems [RAMI 4.0]

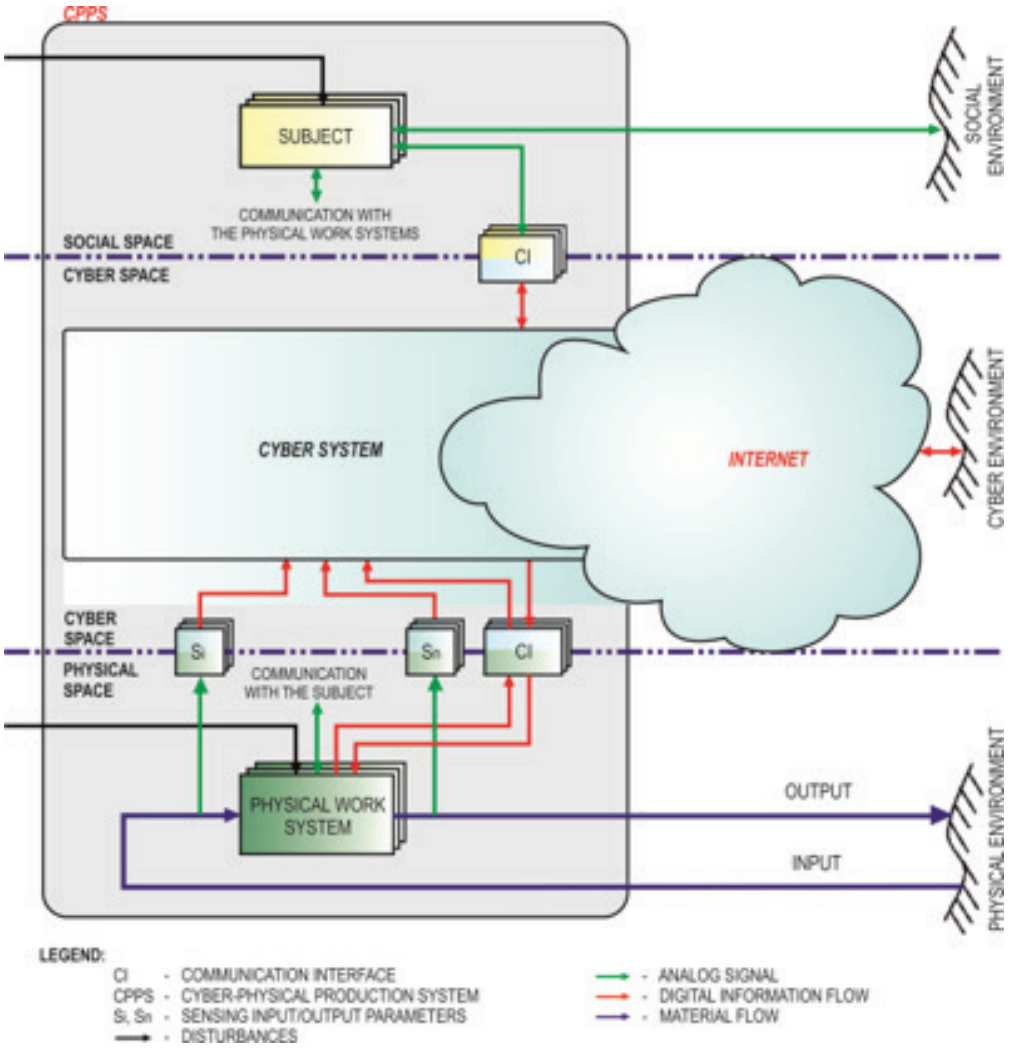


Figure 4: The Cyber-Physical Production System (CPPS) Model [31]

The growing complexity of manufacturing environments has stimulated the emergence of cognitization as the next stage of industrial evolution. Cognitization extends beyond connectivity and automation by incorporating contextual understanding, learning, reasoning, knowledge generation, and adaptive decision-making capabilities [17,18]. Recent advances in artificial intelligence, cognitive computing, Cognitive Digital Twins (CDT), and Human Digital Twins (HDT) provide the technological foundation for this transformation [19,40–42]. Figure 5 illustrates the evolution of manufacturing intelligence from mechanization toward cognitization.

The progressive development of manufacturing capabilities from digitalization through cybernation toward cognitization is summarized in Table 1. While digitalized systems and conventional CPPS provide advanced capabilities in connectivity, monitoring, and predictive analytics, they remain limited in context awareness, reasoning, knowledge generation, adaptive decision-making, and cognitive support for human operators. In contrast, cognitized manufacturing systems introduce these capabilities as core operational functions, enabling the transformation from information-driven systems toward knowledge-driven and continuously learning environments [8,17,18,34].

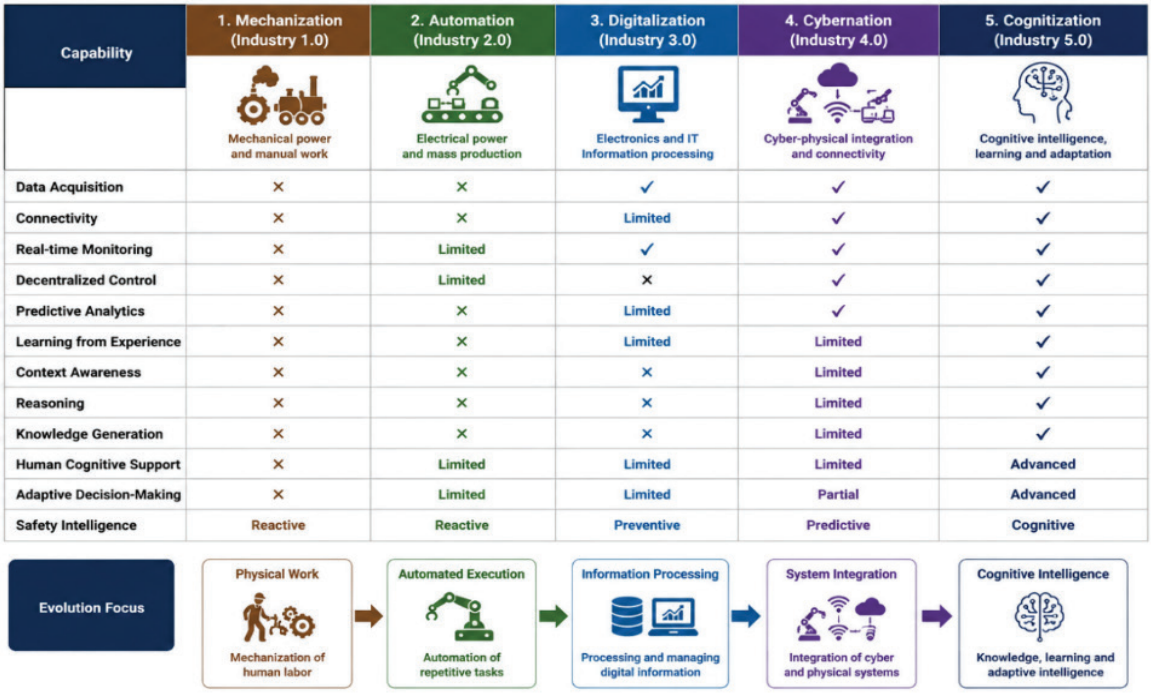


Figure 5: Evolution of Manufacturing Intelligence from Mechanization to Cognitization

Table 1: Comparative Capabilities of Digitalized Systems, CPPS, and Cognitive Manufacturing Systems

Capability	Digitalization	CPPS	Cognitization
Data acquisition	✓	✓	✓
Connectivity	✓	✓	✓
Real-time monitoring	✓	✓	✓
Decentralized control	x	✓	✓
Predictive analytics	Limited	✓	✓
Learning from experience	x	Limited	✓
Context awareness	x	x	✓
Reasoning	x	x	✓

Capability	Digitalization	CPPS	Cognitization
Knowledge generation	x	x	✓
Human cognitive support	Limited	Limited	Advanced
Adaptive decision-making	Limited	Partial	Advanced
Safety intelligence	Reactive	Predictive	Cognitive
Human–AI Collaboration	x	Limited	Advanced
Human Digital Twin Integration	x	x	✓

The technological realization of cognitization is represented by C-CPPS. These systems integrate cyber-physical infrastructures, artificial intelligence, CDT, HDT, and human-centered decision-making mechanisms within a unified operational environment [17–19,27,41–44]. Unlike conventional CPPS, C-CPPS are capable of contextual reasoning, knowledge generation, continuous learning, and adaptive decision-making. Figure 6 presents the conceptual architecture of a C-CPPS [20].

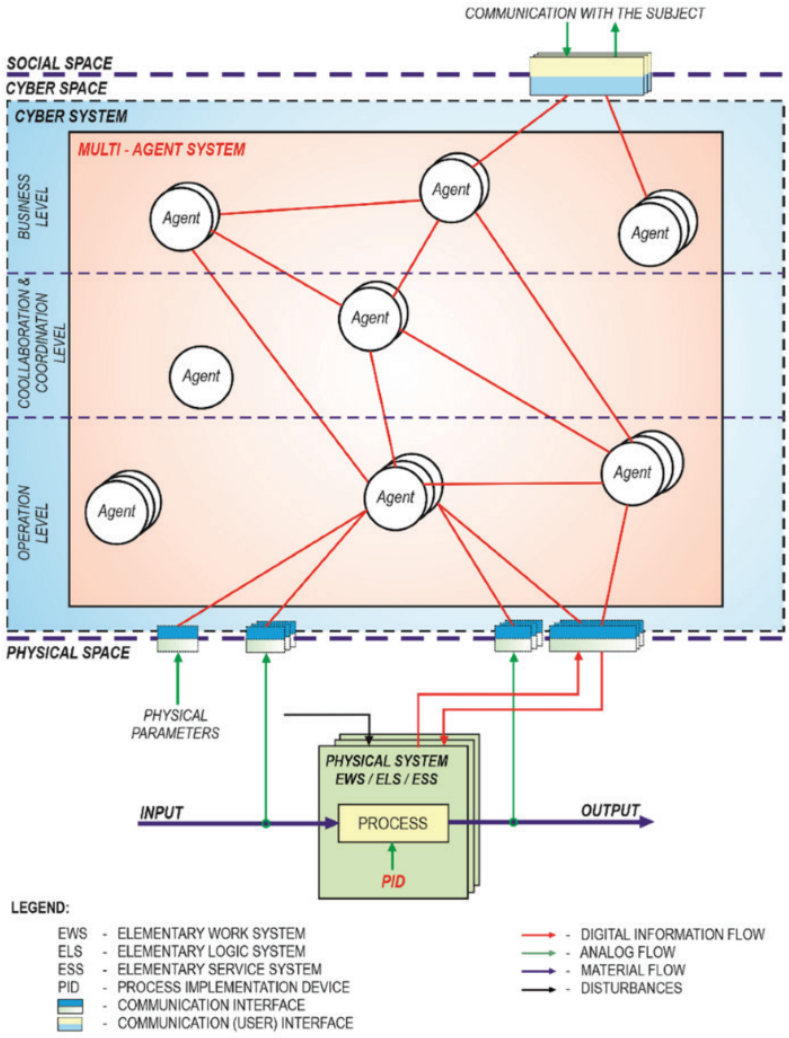


Figure 6: Conceptual Architecture of a Cognitive Cyber-Physical Production System (C-CPPS) [20]

A defining characteristic of C-CPPS is the transition from human–machine interaction toward Human–AI collaboration. Artificial intelligence functions as a cognitive assistant that supports operators through information processing, predictive analytics, pattern recognition, and decision recommendations, while humans remain responsible for contextual interpretation, ethical judgment,

strategic decisions, and system oversight [13–16,34,40, 45–47]. Through continuous cognitive feedback loops, operational data are transformed into information, information into knowledge, and knowledge into adaptive actions.

The principal differences between conventional CPPS and C-CPPS are summarized in Table 2. The introduction of context awareness, reasoning, knowledge generation, HDT and CDT integration, Human–AI collaboration, and cognitive safety capabilities clearly distinguishes C-CPPS from previous manufacturing paradigms.

Table 2: Comparison of CPPS and C-CPPS Capabilities

Capability	CPPS	C-CPPS
Monitoring	✓	✓
Predictive Analytics	✓	✓
Decentralized Control	✓	✓
Context Awareness	x	✓
Reasoning	x	✓
Knowledge Generation	x	✓
Learning from Experience	Limited	Advanced
Human Digital Twin Integration	x	✓
Cognitive Digital Twin Integration	x	✓
Human–AI Collaboration	Limited	Advanced
Adaptive Decision-Making	Partial	Advanced
Safety Intelligence	Predictive	Cognitive

Overall, the evolution from mechanization to cognitization reflects a gradual shift from physical automation and information processing toward knowledge-driven, adaptive, and continuously learning manufacturing systems. By integrating cyber-physical infrastructures, artificial intelligence, HDT, CDT, and human-centered decision-making mechanisms, C-CPPS establish the technological foundation for the emerging Safety 5.0 paradigm discussed in the following chapter.

3. EVOLUTION OF OCCUPATIONAL SAFETY: FROM SAFETY 1.0 TO SAFETY 5.0

The evolution of occupational safety has closely followed the technological development of manufacturing systems. As industrial environments became increasingly complex, safety management evolved from reactive accident investigation toward predictive, adaptive, and human-centric approaches. Figure 7 illustrates the parallel evolution of manufacturing systems and occupational safety paradigms, highlighting the progression from Safety 1.0 to the emerging Safety 5.0 concept.

The earliest stage of occupational safety, referred to as Safety 1.0, emerged during the industrialization period and focused primarily on accident investigation, injury reduction, and corrective actions following incidents [48]. Safety performance was typically evaluated through accident statistics and injury indicators, while workplace accidents were largely attributed to unsafe acts and human error. Heinrich's Domino Theory, illustrated in Figure 8, represents one of the foundational models of this period [48,49].

As industrial systems became more structured and regulated, Safety 2.0 introduced preventive approaches based on hazard identification, risk assessment, and regulatory compliance [50]. The focus shifted from accident response toward accident prevention through systematic risk management and implementation of control measures. Figure 9 illustrates the hierarchy of controls, which remains one of the fundamental frameworks for occupational risk reduction. Table 3 summarizes the principal differences between the reactive philosophy of Safety 1.0 and the preventive orientation of Safety 2.0.

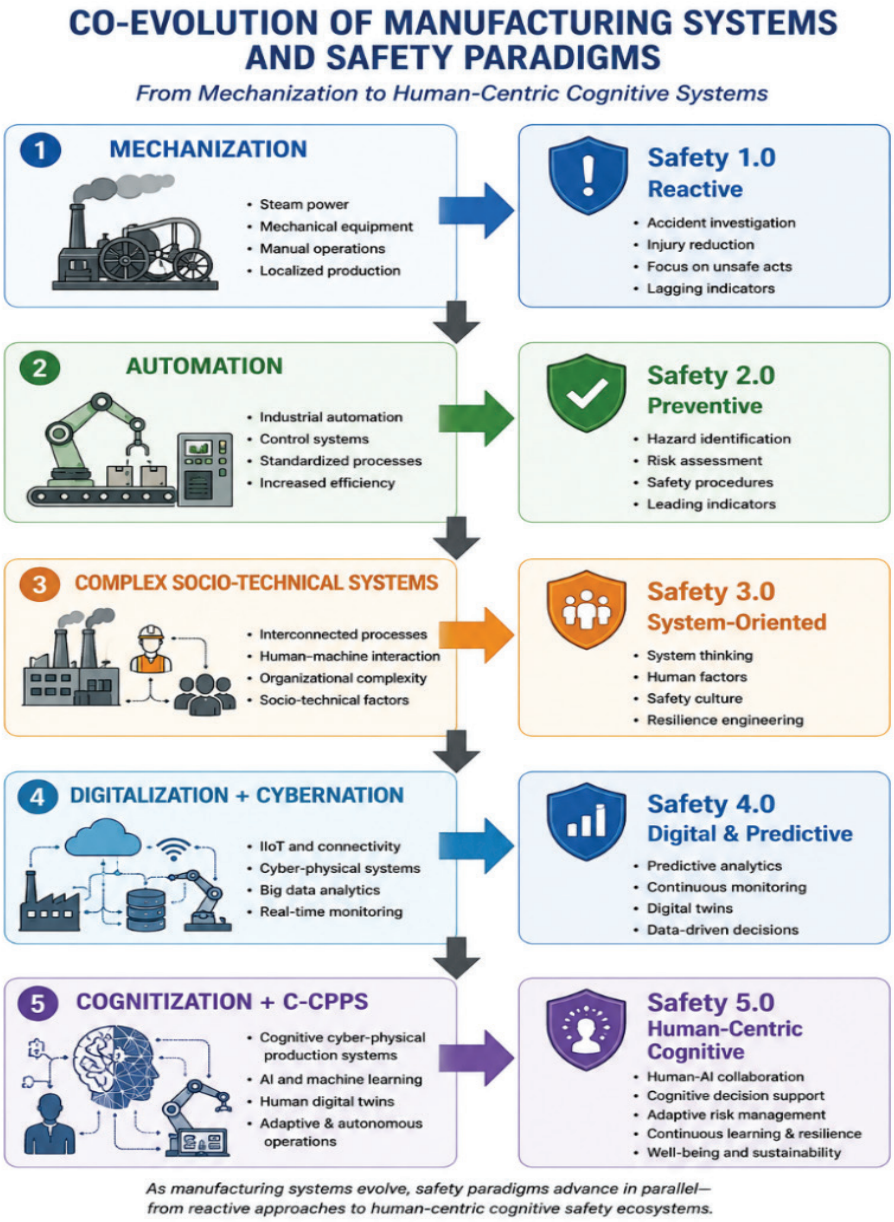


Figure 7: Co-Evolution of Manufacturing Systems and Occupational Safety Paradigms

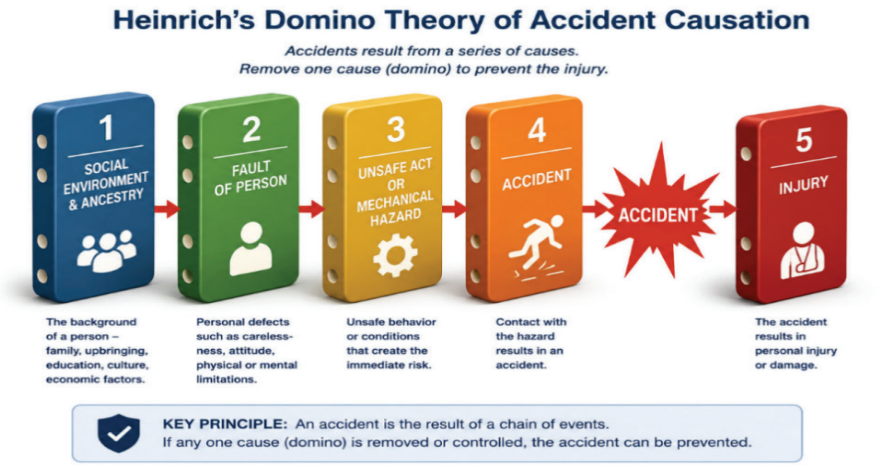


Figure 8: Heinrich's Domino Theory of Accident Causation

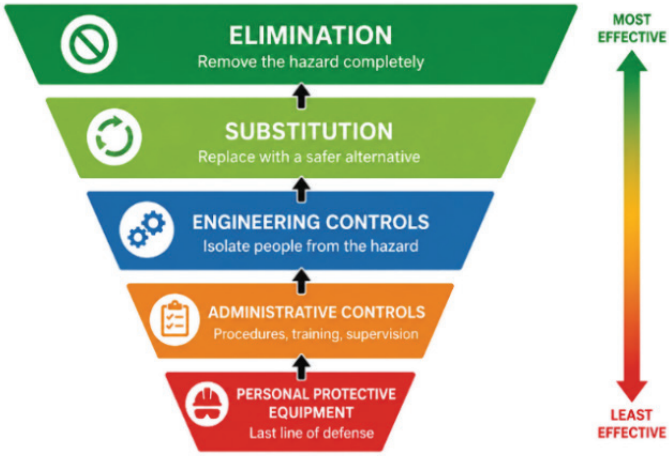


Figure 9: Hierarchy of Controls as the Fundamental Prevention Framework of Safety 2.0

Table 3: Comparison of Safety 1.0 and Safety 2.0

Aspect	Safety 1.0	Safety 2.0
Philosophy	Reactive	Preventive
Focus	Accident investigation	Risk prevention
Main Tools	Accident statistics	Risk assessment
Human Role	Source of error	Participant in prevention
Safety Indicators	LTIFR, TRIR	Risk controls and compliance
Management Approach	Corrective	Preventive

The increasing complexity of industrial systems subsequently stimulated the development of Safety 3.0, which introduced a systems-oriented perspective on safety management [10,36,52–55]. Rather than viewing accidents as isolated events, Safety 3.0 considers safety as an emergent property of socio-technical systems. Human operators became recognized not only as potential sources of error but also as contributors to resilience, adaptability, and safe system performance. The Swiss Cheese Model shown in Figure 10 illustrates this transition from individual failure analysis toward understanding interactions among organizational, technical, and human factors [36]. The principal characteristics of Safety 3.0 are summarized in Table 4.

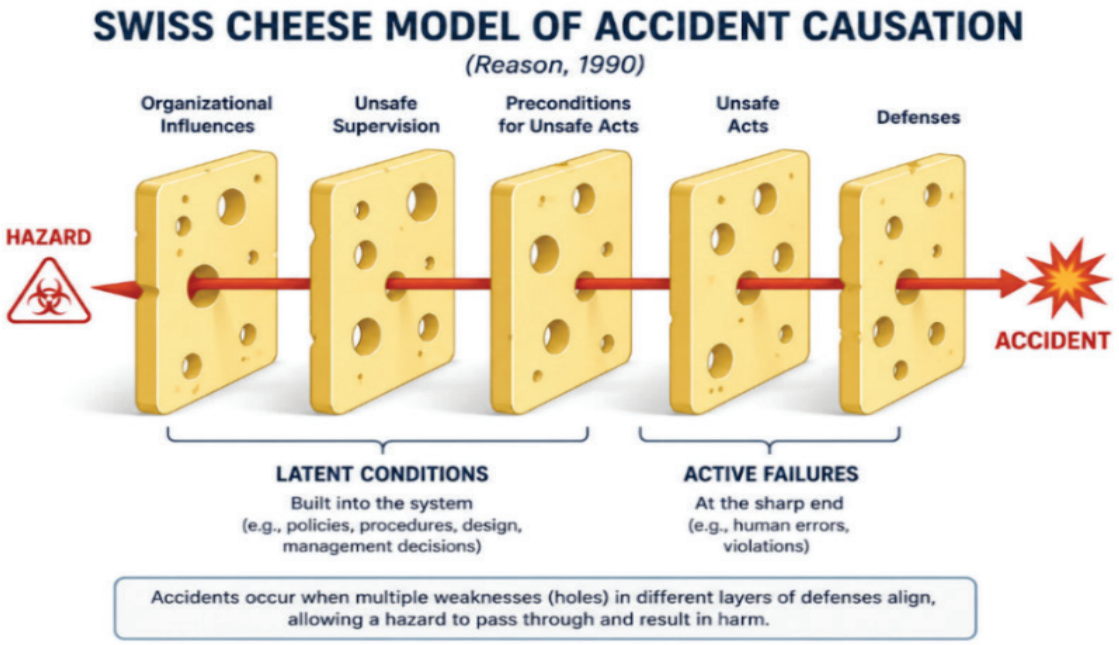


Figure 10: Swiss Cheese Model of Accident Causation [36]

Table 4: Key Characteristics of Safety 3.0

Dimension	Safety 3.0
Safety Philosophy	System-oriented
Accident Causation	Emergent property of socio-technical systems
Human Role	Contributor to resilience and adaptability
Key Concepts	Human factors, safety culture, resilience
Primary Models	Swiss Cheese Model, Socio-Technical Systems
Main Objective	Understanding systemic interactions
Management Approach	Organizational learning and resilience

The emergence of Industry 4.0 enabled the development of Safety 4.0 through the integration of IIoT, cyber-physical systems, cloud computing, artificial intelligence, big data analytics, and digital twins [17,23,26–29]. These technologies support continuous monitoring, predictive analytics, anomaly detection, and proactive risk assessment. Figure 11 illustrates the digital safety architecture characteristic of Safety 4.0. Despite these advances, most Safety 4.0 implementations remain focused on monitoring and prediction, providing limited support for contextual understanding, adaptive reasoning, and effective Human–AI collaboration.

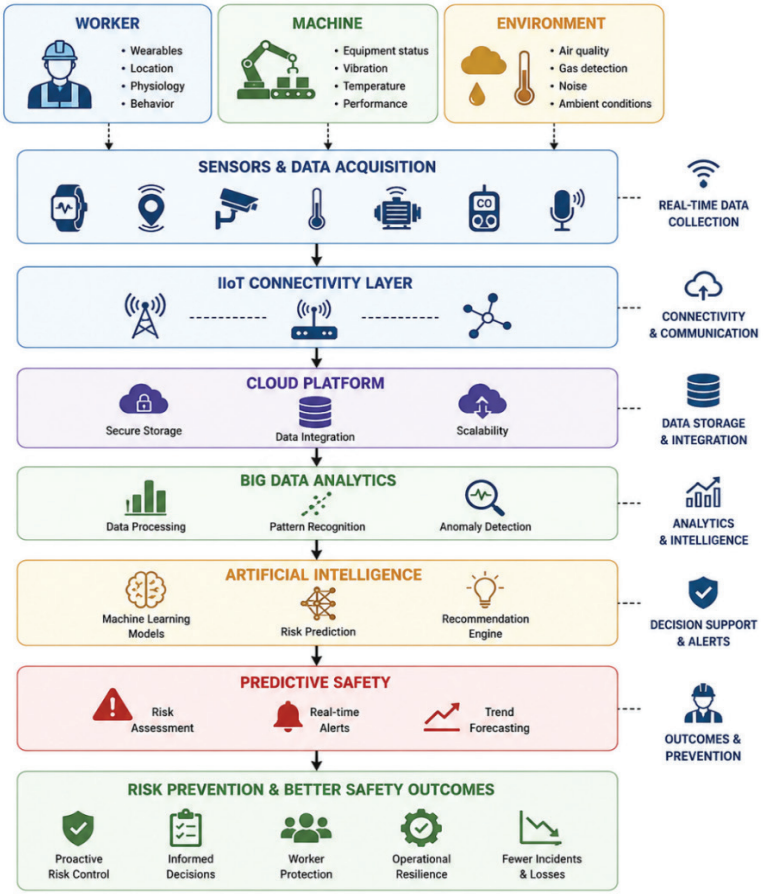


Figure 11: Digital Safety Architecture in Safety 4.0.

The growing complexity of socio-cyber-physical environments, together with the emergence of Industry 5.0 and cognitization, has stimulated the development of Safety 5.0. Unlike previous safety paradigms, Safety 5.0 integrates human intelligence, AI, HDT, CDT, and C-CPPS within a unified human-centric safety ecosystem [13–20]. The objective is not only to predict risks but also to understand context, support adaptive decision-making, and enhance resilience through continuous collaboration between humans and intelligent technologies.

A central concept within Safety 5.0 is Safety Intelligence (SI), which may be defined as the capability of intelligent socio-cyber-physical safety systems to continuously transform data into information, information into knowledge, and knowledge into adaptive safety actions through the integration of artificial intelligence, cognitive digital twins, human expertise, and organizational learning mechanisms. Through contextual reasoning, adaptive learning, and human oversight, SI enables safety systems not only to identify hazards but also to interpret their significance and support proactive interventions under dynamic operating conditions.

From an evolutionary perspective, Safety Intelligence (SI) may be viewed as the cognitive extension of predictive safety. While Safety 4.0 primarily relies on data-driven monitoring, anomaly detection, and risk prediction, SI extends these capabilities through contextual reasoning, knowledge generation, adaptive learning, and Human–AI collaboration. Consequently, the transition from predictive safety to Safety Intelligence represents a shift from anticipating risks toward understanding their context, evaluating alternative responses, and supporting adaptive safety decision-making under dynamic operating conditions.

Safety 5.0 is also strongly aligned with Resilience Engineering (RE) and Safety-II thinking, which emphasize understanding how systems maintain successful performance under varying and uncertain conditions rather than focusing exclusively on failure prevention. Consequently, human adaptability, organizational learning, and intelligent decision support become central contributors to sustainable safety performance.

Figure 12 presents the proposed Human-Centric Cognitive Safety Architecture, illustrating how Safety 5.0 emerges through the integration of C-CPPS, AI, HDT, CDT, and Safety Intelligence within a socio-cyber-physical environment. The principal differences between Safety 4.0 and Safety 5.0 are summarized in Table 5.

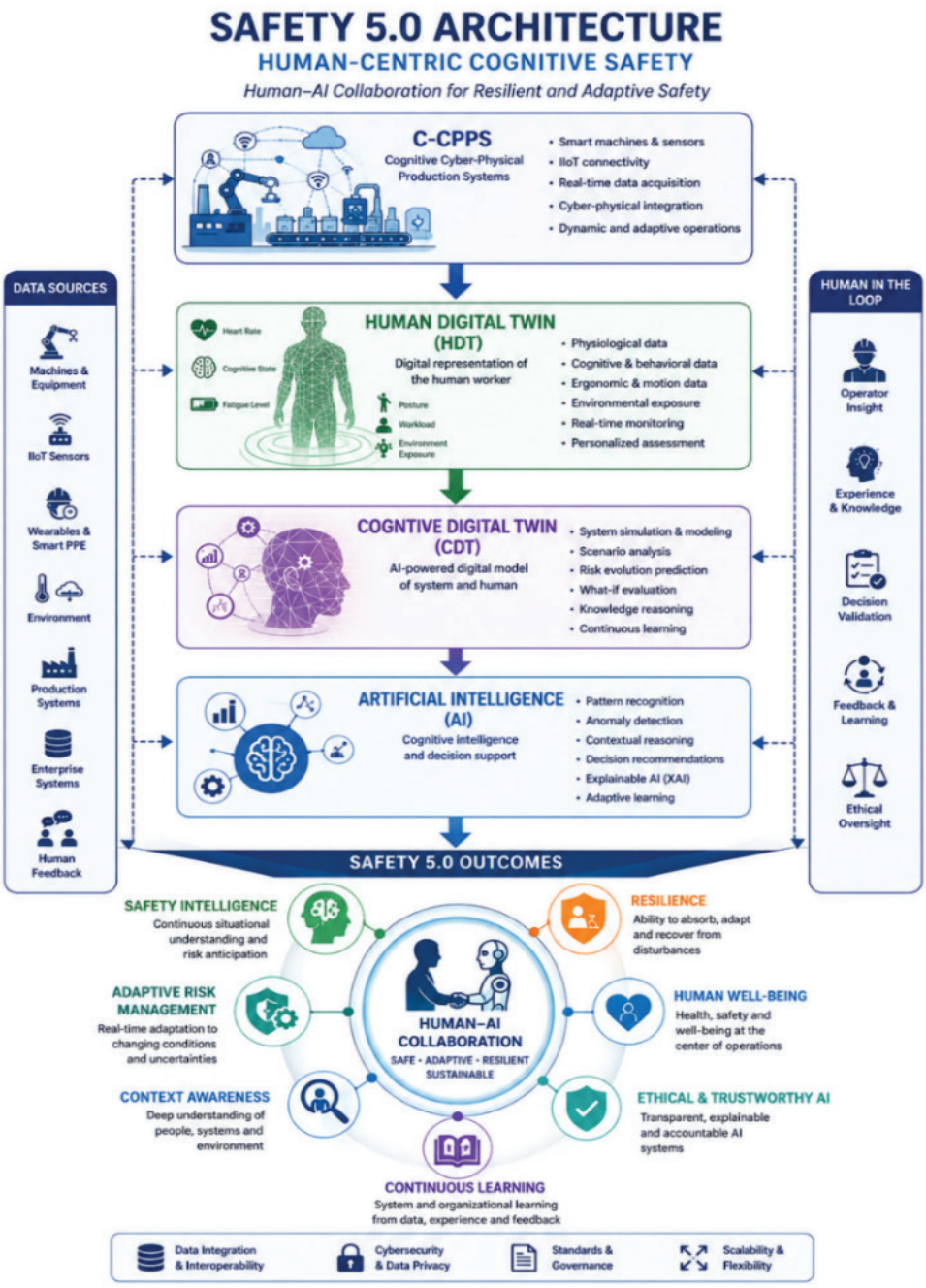


Figure 12: Human-Centric Cognitive Safety Architecture (Safety 5.0)

Table 5: Comparison of Safety 4.0 and Safety 5.0

Aspect	Safety 4.0	Safety 5.0
Primary Focus	Monitoring and Prediction	Cognition and Adaptation
Human Role	System User	Cognitive Partner
Artificial Intelligence	Predictive Analytics	Contextual Reasoning
Digital Twin	Monitoring and Simulation	Cognitive Digital Twin
Risk Assessment	Predictive	Adaptive and Context-Aware
Decision-Making	AI-Assisted	Human–AI Collaborative
Learning Capability	Data-Driven	Knowledge-Driven
Safety Philosophy	Predictive Safety	Cognitive and Resilient Safety
Worker Well-being	Secondary Objective	Central Objective
Industry Paradigm	Industry 4.0	Industry 5.0

Overall, the evolution from Safety 1.0 to Safety 5.0 reflects a transition from reactive accident management toward cognitive, adaptive, and human-centric safety ecosystems. As manufacturing systems evolve toward intelligent socio-cyber-physical environments, safety management must likewise evolve beyond compliance and prediction toward contextual understanding, collaborative intelligence, resilience, and continuous learning.

4. TOWARD SAFETY 5.0: A HUMAN-CENTRIC COGNITIVE SAFETY FRAMEWORK

4.1. Conceptual Foundation of Safety 5.0

The preceding chapters demonstrated that the evolution of occupational safety has closely followed the technological evolution of industrial systems. From reactive accident investigation in Safety 1.0 to predictive and digitalized safety management in Safety 4.0, each safety paradigm emerged in response to increasing technological complexity and changing operational requirements. However, the growing integration of artificial intelligence, cyber-physical systems, digital twins, and human-centered Industry 5.0 principles has created new challenges that cannot be fully addressed by existing safety management approaches.

Although Safety 4.0 introduced significant advances in real-time monitoring, predictive analytics, and data-driven decision support, its primary focus remains centered on information processing and prediction. Most digital safety systems are capable of identifying hazards, detecting anomalies, and estimating future risks; however, they often lack contextual understanding, adaptive reasoning, and the ability to support collaborative decision-making between human operators and intelligent technologies. Consequently, predictive capabilities alone are insufficient for managing the complexity of modern socio-cyber-physical production environments.

The emergence of cognitization and C-CPPS provides an opportunity to overcome these limitations. By integrating AI, CDT, HDT, and adaptive learning mechanisms, manufacturing systems become capable of transforming operational data into contextual knowledge and actionable intelligence. This transformation enables safety management systems not only to predict adverse events but also to understand their underlying causes, evaluate alternative responses, and continuously improve decision quality through experience.

A fundamental premise of Safety 5.0 is that occupational safety should no longer be viewed exclusively as a technical or regulatory function. Instead, safety must be understood as an emergent property of intelligent socio-cyber-physical systems in which human intelligence and artificial intelligence interact continuously. Within this perspective, human operators are regarded as active cognitive partners rather than passive system users or potential sources of error. Human expertise, situational awareness, ethical judgment, creativity, and adaptive problem-solving capabilities therefore become integral components of future safety management systems.

Figure 13 illustrates the conceptual foundations of Safety 5.0.

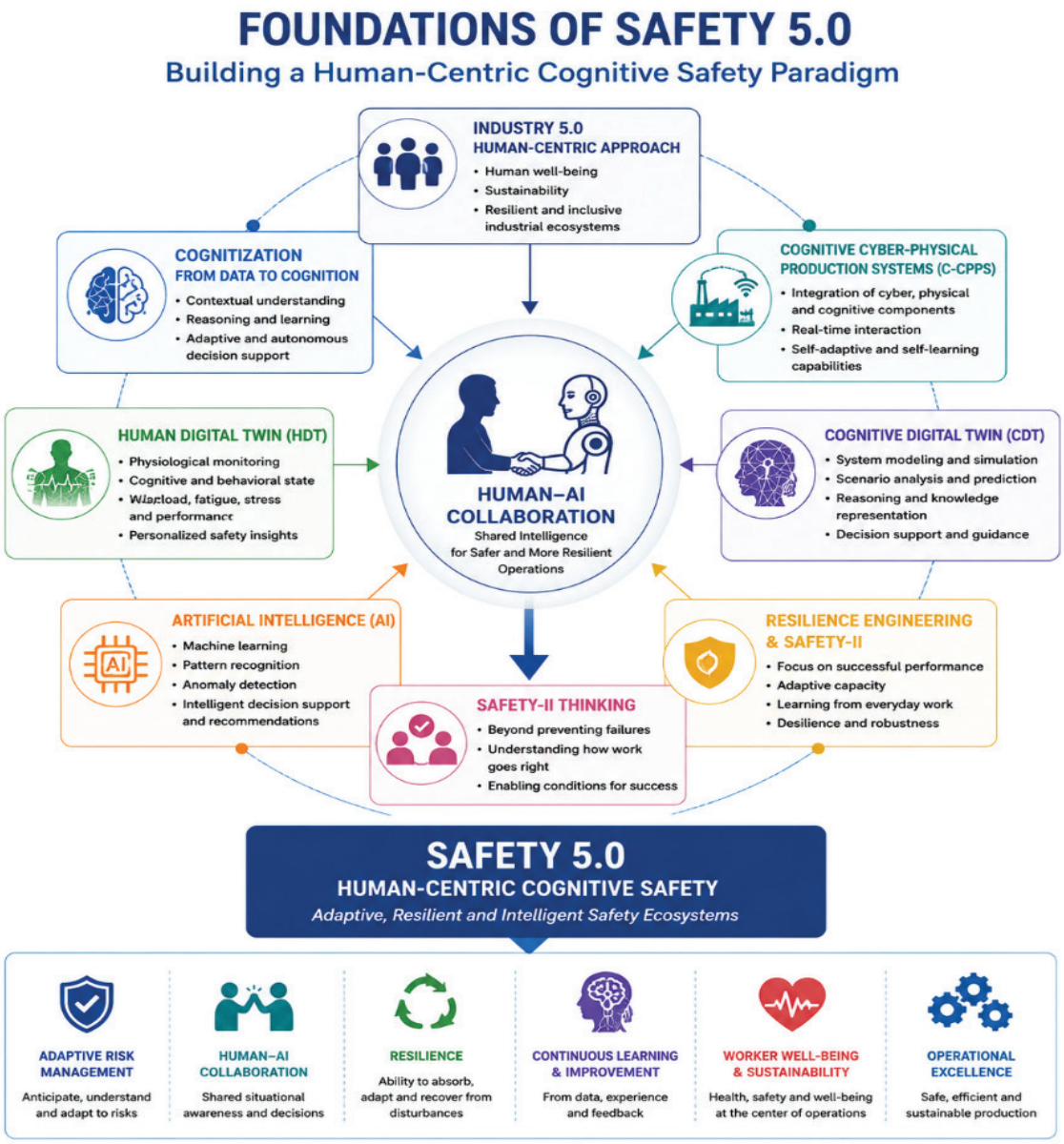


Figure 13: Foundations of Safety 5.0

The framework demonstrates how Industry 5.0 principles, cognitization, C-CPPS, HDT, CDT, AI, Resilience Engineering (RE), and Safety-II thinking collectively contribute to the development of human-centric cognitive safety ecosystems. At the center of the framework lies Human–AI collaboration, which enables adaptive risk management, continuous learning, resilience, and improved worker well-being.

The concept of Safety 5.0 is further supported by recent developments in resilience engineering and Safety-II thinking. Rather than focusing solely on preventing failures, resilient organizations seek to understand how systems maintain safe performance under varying operational conditions. This perspective shifts attention from accident causation toward adaptive capacity, organizational learning, and the ability to respond effectively to uncertainty. Consequently, future safety systems must be capable of supporting not only risk reduction but also resilience enhancement and continuous performance improvement.

Another important foundation of Safety 5.0 is the emergence of HDT and CDT. The HDT provide dynamic representations of worker physiological, cognitive, and behavioral characteristics, enabling intelligent safety systems to assess fatigue, workload, stress, situational awareness, and ergonomic conditions. The CDT extend traditional digital twin concepts by incorporating reasoning, learning, knowledge representation, and decision-support capabilities. Together, HDT and CDT establish the technological foundation for adaptive and human-centered safety management.

An emerging concept associated with Safety 5.0 is Safety Intelligence, which refers to the capability of intelligent socio-cyber-physical safety systems to continuously transform data into information, information into knowledge, and knowledge into adaptive safety actions. Safety Intelligence combines artificial intelligence, cognitive digital twins, human expertise, and organizational learning mechanisms to support contextual understanding, adaptive risk management, and proactive decision-making. Consequently, safety management evolves beyond prediction and prevention toward continuous cognitive awareness and intelligent intervention.

Based on these developments, Safety 5.0 may be defined as a human-centric cognitive safety paradigm that integrates human intelligence, AI, C-CPPS, HDT, and CDT to support adaptive, resilient, explainable, and continuously learning occupational safety ecosystems.

The conceptual framework proposed in this study builds upon these foundations and aims to provide a structured model for integrating cognitive technologies, human-centered principles, and intelligent decision-support mechanisms within future occupational safety management systems. The overall architecture of the proposed Human-Centric Cognitive Safety Framework is presented in the following section, where the interactions among HDT, CDT, AI, and C-CPPS are formalized within a unified Safety 5.0 model.

4.2. Proposed Human-Centric Cognitive Safety Framework

Building upon the conceptual foundations presented in the previous section, this study proposes a Human-Centric Cognitive Safety Framework designed to support the implementation of Safety 5.0 within intelligent manufacturing environments. The proposed framework integrates human intelligence, artificial intelligence, HDT, CDT, and C-CPPS into a unified socio-cyber-physical safety ecosystem capable of adaptive, resilient, and continuously learning safety management.

The proposed framework is based on the premise that occupational safety should be understood as a dynamic and continuously evolving process emerging from interactions among human operators, intelligent technologies, organizational knowledge, and physical production environments. Consequently, safety management extends beyond traditional risk assessment and hazard control toward contextual understanding, adaptive decision-making, and continuous organizational learning.

The architecture of the proposed framework consists of five mutually interconnected layers, as illustrated in Figure 14. The framework integrates physical production environments, HDT, CDT, AI, and Safety Intelligence (SI) within a unified socio-cyber-physical ecosystem. Operational information

originating from machines, processes, workers, and sensors is continuously transformed into contextual knowledge through cognitive modeling and AI. Human–AI collaboration functions as the central decision-making mechanism, enabling adaptive safety actions based on both computational intelligence and human expertise. Through continuous feedback and learning loops, the framework supports adaptive risk management, worker well-being, organizational resilience, explainable decision support, continuous learning, and proactive safety interventions.

The first layer represents the Physical Environment Layer, which includes manufacturing equipment, production processes, environmental conditions, operational resources, and human operators. This layer continuously generates operational information related to machine states, environmental parameters, worker activities, and safety-critical events. Sensors, wearable technologies, smart personal protective equipment, and IIoT infrastructures enable continuous acquisition of relevant safety information.

The second layer corresponds to the HDT Layer. The HDT create dynamic digital representations of workers by integrating physiological, cognitive, behavioral, ergonomic, and environmental information. Through continuous monitoring and modeling, HDT enable intelligent safety systems to evaluate worker fatigue, workload, stress levels, situational awareness, ergonomic conditions, and overall well-being. This capability supports personalized safety interventions and human-centered risk management.

The third layer consists of CDT. Unlike conventional digital twins focused primarily on monitoring and simulation, CDT incorporate artificial intelligence, knowledge models, learning mechanisms, and reasoning capabilities. CDT continuously interpret operational information, evaluate alternative scenarios, identify emerging risks, and support adaptive decision-making processes. Through these capabilities, CDT transform operational data into contextual knowledge relevant for safety management.

The fourth layer represents the AI and SI layer. The AI algorithms continuously process information originating from HDT, CDT, and physical production environments. Machine learning, deep learning, reinforcement learning, and generative AI technologies support anomaly detection, risk prediction, scenario evaluation, and decision optimization. At this level, SI emerges as the capability to transform data into information, information into knowledge, and knowledge into adaptive safety actions.

To ensure transparency and trustworthiness, Safety Intelligence mechanisms should incorporate Explainable Artificial Intelligence (XAI) principles. XAI enables human operators to understand the rationale behind AI-generated recommendations, thereby supporting trust, accountability, and effective human oversight.

The fifth layer corresponds to the Human–AI Collaboration Layer. This layer represents the central component of the proposed framework and distinguishes Safety 5.0 from previous safety paradigms. Rather than replacing human expertise, artificial intelligence functions as a cognitive assistant supporting human decision-making. Human operators contribute contextual understanding, ethical judgment, creativity, and strategic reasoning, while artificial intelligence contributes analytical capabilities, predictive insights, and continuous information processing. Together, they form a collaborative intelligence environment capable of supporting adaptive and resilient safety management.

An important characteristic of the proposed framework is the presence of continuous feedback loops connecting all architectural layers. Information generated through adaptive safety actions and Human–AI collaboration is continuously incorporated into HDT, CDT, and SI mechanisms.

Consequently, the framework supports not only safety management but also continuous organizational learning and long-term knowledge evolution.

The interaction among these layers enables the continuous assessment of operational conditions, identification of emerging hazards, contextual interpretation of safety information, and implementation of adaptive interventions. Through continuous learning and feedback mechanisms, the framework supports the evolution of organizational knowledge and the improvement of safety performance over time.

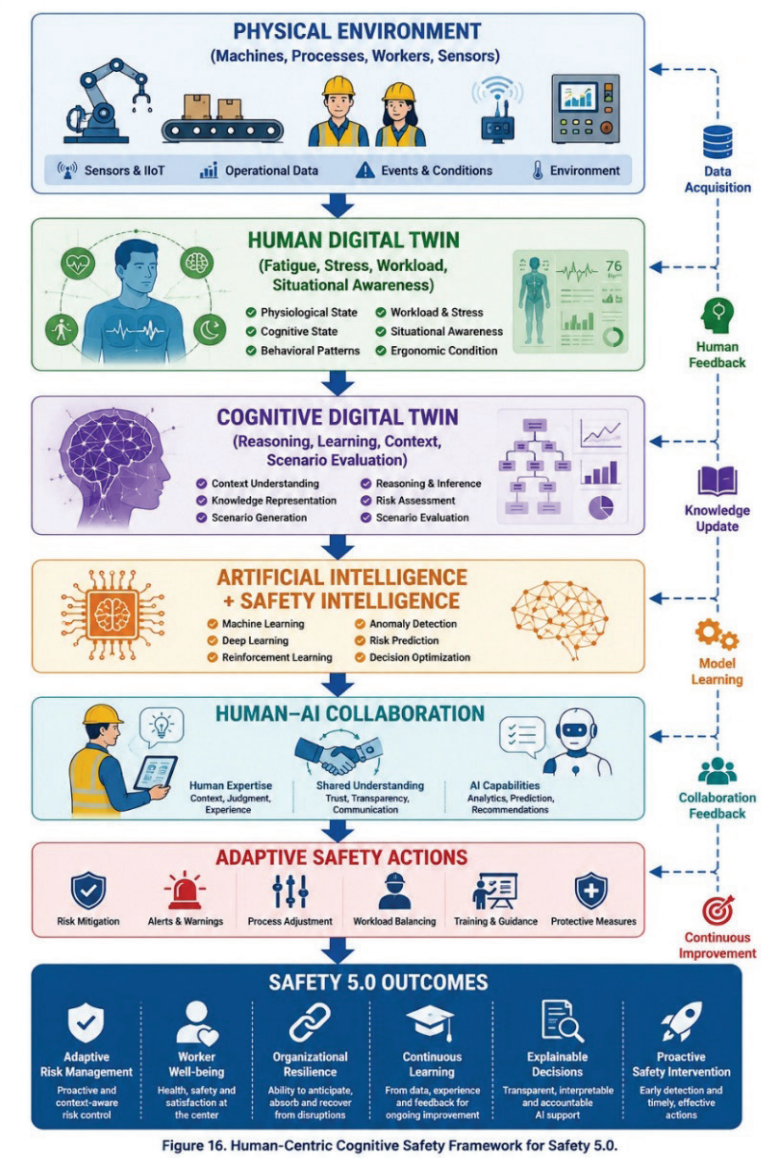


Figure 16. Human-Centric Cognitive Safety Framework for Safety 5.0.

Figure 14: Human-Centric Cognitive Safety Framework for Safety 5.0

The proposed Human-Centric Cognitive Safety Framework ultimately contributes to several Safety 5.0 outcomes, including adaptive risk management, improved situational awareness, enhanced worker well-being, increased organizational resilience, continuous learning, explainable decision support, and proactive safety intervention. Consequently, the framework provides a practical pathway for transforming traditional safety management systems into intelligent, human-centered, and cognitively enabled safety ecosystems.

4.3. Key Enablers of Safety 5.0: Human Digital Twins, Cognitive Digital Twins and Safety Intelligence

The implementation of Safety 5.0 relies on three closely interconnected technological enablers: HDT, CDT, and SI. Together, these technologies establish the human-centric cognitive capabilities required for adaptive, resilient, and continuously learning occupational safety management systems.

HDT represent the human-centered component of Safety 5.0. Unlike conventional safety systems that primarily focus on equipment, hazards, and environmental conditions, HDT provide continuously synchronized digital representations of workers by integrating physiological, cognitive, behavioral, ergonomic, and environmental information. Enabled by wearable technologies, smart personal protective equipment, biometric sensors, and location-tracking systems, HDT support real-time assessment of fatigue, workload, stress, situational awareness, and worker well-being. Consequently, safety management evolves from generalized protection strategies toward personalized and adaptive interventions tailored to individual worker conditions and operational contexts. Within the proposed framework, HDT function as the primary interface between human operators and intelligent technologies, supplying contextual information required for adaptive safety decision-making.

Figure 15 illustrates the role of HDT within the proposed Human-Centric Cognitive Safety Framework.

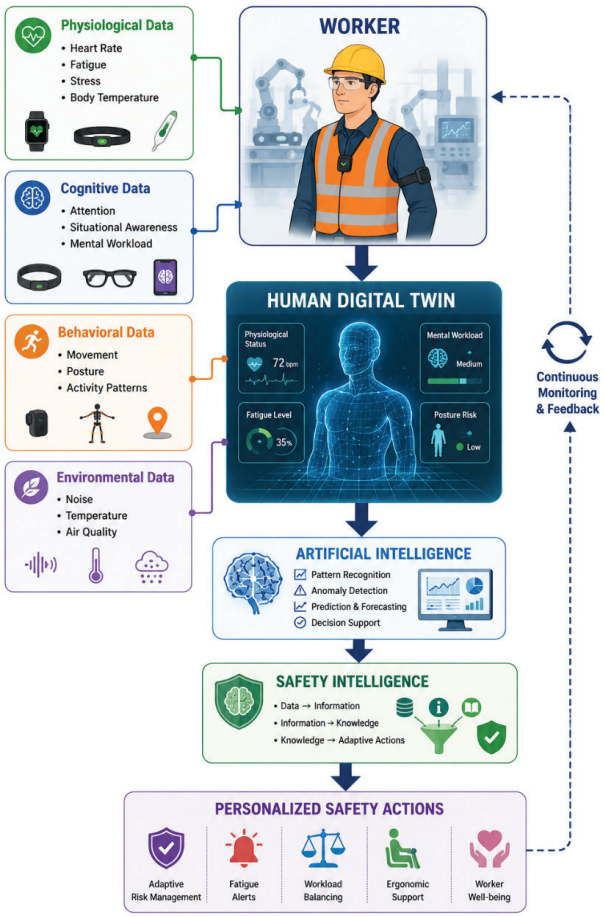


Figure 15: Human Digital Twin Architecture for Safety 5.0

While HDT provide detailed information regarding worker states and capabilities, effective Safety 5.0 implementation additionally requires mechanisms capable of interpreting this information and transforming it into contextual understanding. This role is fulfilled by CDT.

CDT extend conventional digital twins beyond monitoring, simulation, and prediction toward reasoning, learning, knowledge generation, and adaptive decision-making. Through continuous integration of information originating from HDT, production systems, environmental monitoring infrastructures, and organizational knowledge repositories, CDT function as the cognitive core of Safety 5.0. They continuously evaluate operational situations, identify emerging risks, assess alternative scenarios, and support dynamic risk assessment. Unlike traditional digital twins that rely primarily on predefined models, CDT continuously learn from operational experience and transform data into contextual knowledge. Through scenario-based reasoning and knowledge generation, they enable proactive and adaptive safety management under changing operational conditions.

Figure 16 illustrates the role of CDT within the proposed Human-Centric Cognitive Safety Framework.

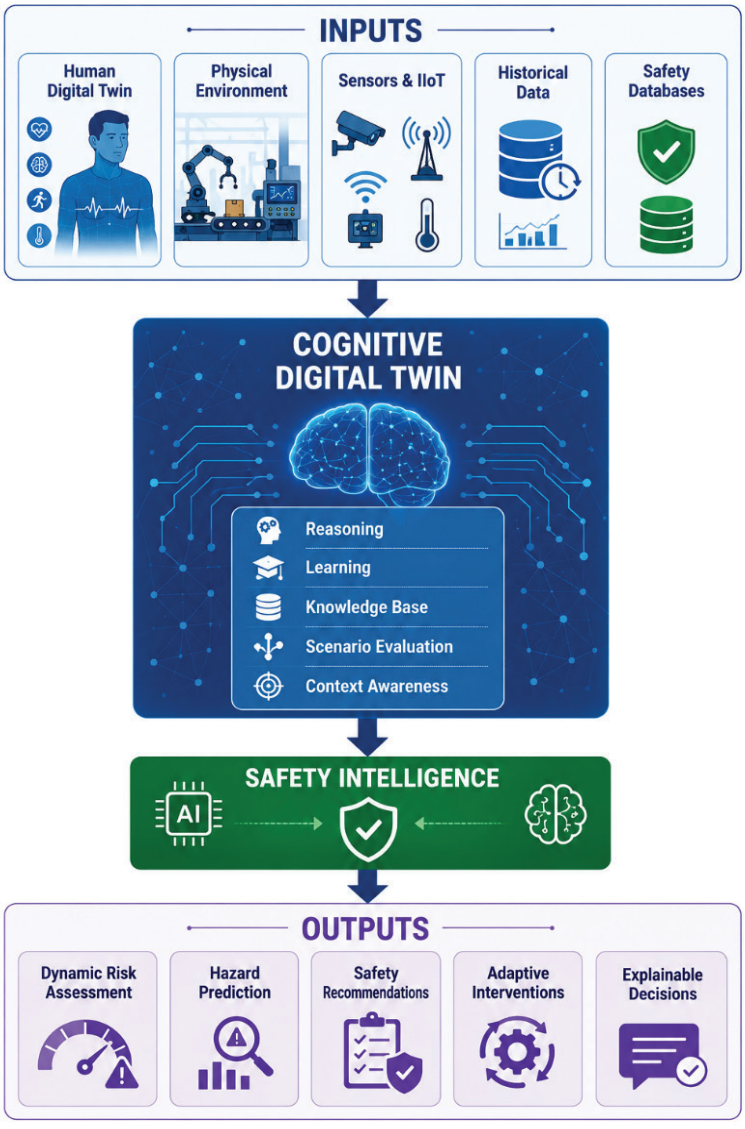


Figure 16: Cognitive Digital Twin Architecture for Safety 5.0

Within the proposed framework, HDT and CDT perform complementary functions. HDT provide real-time information regarding worker physiological, cognitive, and behavioral conditions, while CDT interpret this information within a broader operational context and transform it into actionable safety knowledge. Together, they establish the technological foundation for adaptive, resilient, and human-centered safety management.

Building upon HDT and CDT, SI serves as the operational decision-making mechanism of Safety 5.0. SI may be understood as the capability of intelligent socio-cyber-physical systems to continuously transform data into information, information into knowledge, and knowledge into adaptive safety actions. Unlike conventional safety analytics focused primarily on monitoring and prediction, SI integrates contextual reasoning, continuous learning, organizational knowledge, and human expertise to support intelligent safety management.

A distinguishing characteristic of SI is its ability to combine computational intelligence with human intelligence. Rather than replacing human decision-makers, SI functions as a collaborative mechanism that augments human capabilities through intelligent recommendations, contextual insights, adaptive risk assessment, and explainable decision support. Human operators contribute experience, ethical judgment, creativity, and contextual understanding, while intelligent systems contribute continuous monitoring, predictive analytics, and computational reasoning. Consequently, safety management evolves from predictive monitoring toward adaptive and context-aware decision-making.

An important capability of SI is the incorporation of Explainable Artificial Intelligence (XAI) principles. Since safety-critical decisions require transparency and trust, intelligent safety systems must provide understandable explanations regarding the reasoning behind their recommendations. This enables effective human oversight and supports trustworthy Human–AI collaboration.

Figure 17 illustrates the role of Safety Intelligence within the proposed Human-Centric Cognitive Safety Framework.

A practical example of SI can be observed in a smart manufacturing environment where wearable sensors detect increasing worker fatigue and reduced situational awareness. The HDT identifies changes in worker condition, the CDT evaluates potential operational consequences and predicts an elevated probability of human error, while SI integrates these findings with historical safety knowledge and recommends adaptive interventions such as workload redistribution or temporary task modification. Following human validation, the recommended actions can be implemented before a safety-critical event occurs.

The interaction among HDT, CDT, and SI establishes the technological foundation for adaptive, explainable, and human-centered safety management. Together, these technologies transform occupational safety from reactive intervention and predictive monitoring toward cognitive, resilient, and continuously learning risk management, thereby enabling the realization of fully integrated C-CPSS discussed in the following section.



Figure 17: Safety Intelligence Architecture for Safety 5.0

4.4. Cognitive Cyber-Physical Safety Systems

The integration of HDT, CDT, AI, and SI establishes the foundation for a new generation of occupational safety systems referred to as Cognitive Cyber-Physical Safety Systems (C-CPSS). These systems represent the practical realization of Safety 5.0 by combining human-centered principles, cognitive technologies, and cyber-physical infrastructures within a unified socio-cyber-physical safety ecosystem.

While traditional safety systems focus primarily on hazard identification, risk assessment, accident prevention, and regulatory compliance, C-CPSS extend these capabilities through contextual understanding, adaptive learning, and cognitive decision support. Consequently, safety management evolves from isolated safety functions toward an intelligent and continuously learning process capable of interpreting operational situations, evaluating risks, and supporting proactive interventions.

Within C-CPSS, physical environments, production systems, environmental monitoring infrastructures, wearable technologies, and human operators continuously generate operational information. HDT provide dynamic representations of worker physiological, cognitive, behavioral,

ergonomic, and environmental conditions, while CDT transform operational information into contextual understanding through reasoning, scenario evaluation, and knowledge generation. Safety Intelligence serves as the central decision-making mechanism, integrating information from HDT, CDT, AI systems, and organizational knowledge repositories to support adaptive safety actions.

A defining characteristic of C-CPSS is Human–AI Collaboration. Rather than replacing human expertise, intelligent technologies function as cognitive assistants that augment human perception, reasoning, and decision-making capabilities. Human operators contribute contextual understanding, ethical judgment, experience, and strategic reasoning, while AI contributes analytical capabilities, predictive modeling, and continuous information processing. Together, they create a collaborative intelligence environment capable of supporting resilient and adaptive safety management.

Figure 18 illustrates the conceptual architecture of a C-CPSS. Through continuous interaction among HDT, CDT, AI, and Safety Intelligence mechanisms, operational information is transformed into contextual knowledge and adaptive safety interventions. Feedback generated through safety actions and operational outcomes is subsequently incorporated into system learning processes, enabling continuous improvement of safety performance.

From an occupational safety perspective, C-CPSS provide several important capabilities, including continuous monitoring of technical and human-related safety conditions, adaptive risk assessment, contextual hazard interpretation, explainable decision support, personalized worker protection, proactive intervention planning, organizational learning, and resilience enhancement. These capabilities clearly distinguish C-CPSS from previous generations of occupational safety solutions and establish them as the technological realization of Safety 5.0.

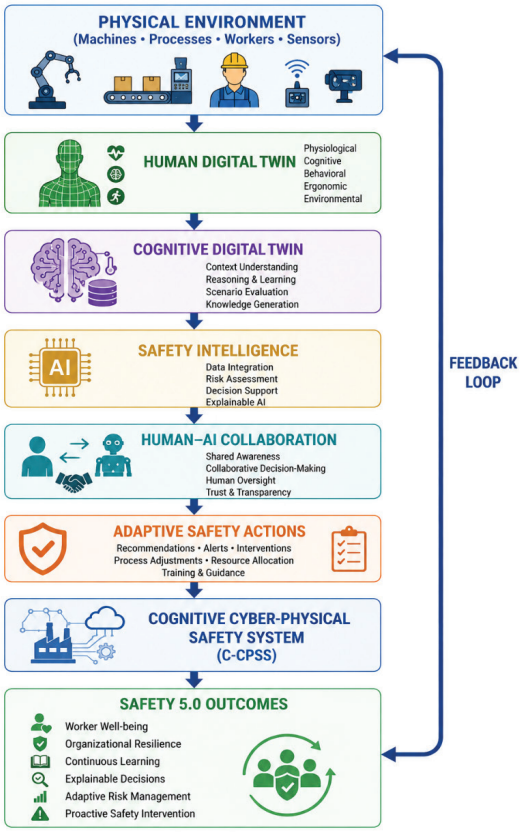


Figure 18: Cognitive Cyber-Physical Safety System (C-CPSS) Architecture for Safety 5.0

Consequently, C-CPSS may be regarded as the operational embodiment of Safety 5.0 and the next evolutionary stage in occupational safety management. By integrating cognitive technologies, human expertise, and intelligent decision-support mechanisms, these systems provide a pathway toward adaptive, explainable, resilient, and human-centered safety ecosystems capable of addressing the complexity of future industrial environments.

Despite their considerable potential, C-CPSS also introduce several challenges that must be addressed before large-scale industrial deployment becomes feasible. These challenges include data privacy and ownership issues associated with HDT, explainability and trustworthiness of AI-supported decisions, interoperability between heterogeneous digital platforms, cybersecurity vulnerabilities, and organizational acceptance of Human–AI collaborative systems. Consequently, the successful implementation of Safety 5.0 requires not only technological advancement but also appropriate organizational, ethical, and regulatory frameworks.

Table 6 summarizes the key concepts that constitute the proposed Human-Centric Cognitive Safety Framework and their relationships within the Safety 5.0 paradigm.

Together, these concepts establish a coherent framework for the transition from conventional safety management toward cognitive, adaptive, and human-centered safety systems. While CPPS provide the technological basis for cyber-physical integration, C-CPPS introduce cognition, learning, and adaptive decision-making. HDT and CDT enable contextual understanding of human and system states, whereas Safety Intelligence and Human–AI Collaboration support informed and proactive safety decisions. Collectively, they form the foundation of the proposed Safety 5.0 paradigm.

Table 6: Key Concepts of the Proposed Safety 5.0 Framework

Concept	Definition
CPPS	Cyber-Physical Production System
C-CPPS	Cognitive Cyber-Physical Production System
HDT	Human Digital Twin
CDT	Cognitive Digital Twin
Safety Intelligence	Cognitive decision-support mechanism
Human–AI Collaboration	Joint decision-making process
Safety 5.0	Human-centric cognitive safety paradigm

5. DISCUSSION, CHALLENGES AND FUTURE DIRECTIONS

5.1. Practical Implications for Industrial Safety Management

The proposed Safety 5.0 framework has significant implications for the future development of occupational safety and health management within intelligent manufacturing environments. Traditional safety management systems have primarily focused on compliance, accident prevention, and risk control through predefined procedures and regulatory requirements. While these approaches remain essential, the increasing complexity of modern socio-cyber-physical production systems requires safety management practices capable of supporting continuous adaptation, contextual understanding, and collaborative decision-making between human operators and intelligent technologies.

The integration of C-CPPS, HDT, CDT, AI, and SI mechanisms enables organizations to move beyond conventional predictive safety approaches toward adaptive and cognitive safety management. In such environments, safety is no longer treated as a static organizational function but rather as a continuously evolving process supported by real-time information, contextual reasoning, and organizational learning [51].

One of the most important practical benefits of the proposed framework is its ability to support personalized safety management. Through HDT, organizations can continuously monitor worker physiological, cognitive, behavioral, and environmental conditions, enabling the identification of fatigue, excessive workload, stress, ergonomic risks, and reduced situational awareness. This capability allows safety interventions to be tailored to individual worker needs, thereby improving worker well-being while simultaneously reducing the likelihood of human-performance-related incidents.

CDT further enhance safety management by transforming operational information into contextual knowledge. Through reasoning, learning, scenario evaluation, and adaptive risk assessment capabilities, CDT enable organizations to evaluate emerging hazards dynamically and recommend appropriate interventions before incidents occur. Consequently, risk management evolves from periodic assessments and static safety procedures toward continuous and context-aware decision-making.

Illustrative Safety 5.0 Use-Case Scenario

Consider a manufacturing operator performing repetitive assembly tasks within a smart production environment. Wearable sensors continuously monitor physiological indicators such as heart rate variability, body temperature, movement patterns, and workload-related parameters. Simultaneously, environmental monitoring systems collect information regarding noise exposure, temperature, air quality, and other workplace conditions.

The HDT continuously analyzes these data and detects increasing fatigue levels accompanied by reduced situational awareness. At the same time, the CDT integrates this information with operational production data, historical incident records, and contextual workplace conditions. Through scenario evaluation and predictive reasoning mechanisms, the CDT identifies an elevated probability of human error during the next production cycle.

The SI subsequently combines these findings with organizational knowledge and existing safety procedures, generating a recommendation for temporary task redistribution and a short recovery period for the affected worker. The recommendation is presented through a Human–AI Collaboration interface to both the operator and the supervisor. Following human validation and approval, the production schedule is adaptively adjusted, workload is redistributed among team members, and the worker is assigned a temporary lower-risk task.

As a result, a potentially hazardous situation is mitigated before an incident occurs. Unlike traditional safety systems that would typically react only after a near miss or accident, the proposed Safety 5.0 framework enables proactive, adaptive, and human-centered intervention based on contextual understanding and collaborative decision-making.

This example illustrates how Safety 5.0 transforms occupational safety management from reactive intervention and predictive monitoring toward cognitive risk understanding and adaptive risk mitigation. More importantly, it demonstrates the complementary relationship between human

expertise and artificial intelligence, where AI supports decision-making while humans remain responsible for contextual interpretation, ethical judgment, and final decision authority.

Beyond personalized interventions, the proposed framework also supports organizational resilience and continuous learning. Through SI mechanisms, operational experiences, near misses, corrective actions, and safety outcomes are continuously transformed into organizational knowledge. This capability enables organizations to improve future decision-making processes, strengthen adaptive capacity, and enhance overall safety performance over time.

Furthermore, the framework contributes to improved worker engagement and safety culture by promoting transparency, collaboration, and trust between human operators and intelligent systems. Rather than replacing human expertise, Safety 5.0 technologies augment human cognitive capabilities, support situational awareness, and facilitate more informed decision-making in complex operational environments.

Consequently, Safety 5.0 should not be viewed merely as a technological advancement but rather as a strategic transformation of occupational safety management toward intelligent, adaptive, resilient, and human-centered safety ecosystems. Through the integration of HDT, CDT, AI, and Human–AI Collaboration mechanisms, organizations can create safer, more sustainable, and more responsive work environments capable of addressing the challenges of next-generation industrial systems.

5.2. Challenges and Limitations of Safety 5.0

Despite its considerable potential, the implementation of Safety 5.0 is associated with several technological, organizational, ethical, and regulatory challenges.

Beyond technological challenges, Safety 5.0 also introduces important organizational and ethical considerations. The deployment of HDT requires organizations to establish transparent governance mechanisms regarding personal data collection, ownership, and usage. Employees must be informed about how physiological and cognitive information is processed and protected. Furthermore, the increasing reliance on artificial intelligence raises questions concerning accountability, transparency, and trust. Organizations must ensure that human operators remain capable of understanding, validating, and overriding AI-generated recommendations when necessary.

Implementation challenges should also not be underestimated. The successful deployment of Safety 5.0 requires significant investments in sensing infrastructures, digital twin technologies, artificial intelligence platforms, cybersecurity mechanisms, and workforce training. Moreover, organizational culture and employee acceptance may become decisive factors influencing the effectiveness of human-centric cognitive safety systems.

One of the most significant challenges concerns data privacy and worker acceptance. HDT rely on continuous acquisition of physiological, cognitive, behavioral, and environmental information. The collection and processing of such data may raise concerns regarding privacy, transparency, and employee trust. Consequently, future Safety 5.0 systems must comply with relevant legal and ethical requirements while ensuring responsible data governance.

Another important challenge relates to explainability and trust in artificial intelligence. As intelligent safety systems become increasingly involved in operational decision-making, human operators must remain capable of understanding the rationale behind AI-generated recommendations. XAI therefore represents a critical requirement for effective Human–AI collaboration.

Cybersecurity constitutes an additional challenge. The extensive interconnectivity characteristic of C-CPSS increases exposure to cyber threats that may compromise operational safety, data integrity, and system reliability. Robust cybersecurity mechanisms must therefore become an integral component of future Safety 5.0 architectures.

Interoperability also remains a major obstacle. HDT, CDT, AI systems, wearable technologies, and industrial information systems often operate on heterogeneous platforms and communication protocols. The absence of standardized architectures may hinder large-scale implementation and integration.

Although the proposed Safety 5.0 framework provides a comprehensive conceptual foundation for future human-centric safety systems, several limitations remain. The effectiveness of HDT and CDT depends heavily on the availability, quality, and reliability of operational data. Furthermore, the proposed framework has not yet been validated through industrial case studies or large-scale implementation scenarios. Consequently, its practical applicability, scalability, and long-term effectiveness require further investigation through empirical research and real-world deployment.

5.3. Future Research Directions

The transition toward Safety 5.0 creates significant opportunities for future research at the intersection of occupational safety, AI, DT, C-CPSS, and Industry 5.0. While the proposed Human-Centric Cognitive Safety Framework establishes a conceptual foundation for next-generation safety management, further research is required to validate, refine, and industrially implement the proposed concepts.

A key research priority is the empirical validation of the framework. Although the proposed architecture is grounded in existing developments related to HDT, CDT, AI, and C-CPSS, its practical effectiveness must be demonstrated through industrial applications. A structured validation roadmap may include four stages:

- Simulation-Based Validation – evaluation of Safety 5.0 concepts in virtual environments and safety-critical scenarios.
- Laboratory-Scale Experiments – testing HDT, wearable technologies, fatigue detection, workload assessment, and adaptive safety interventions.
- Pilot Industrial Implementation – deployment of selected Safety 5.0 components in smart manufacturing environments to evaluate Human–AI Collaboration and adaptive risk management.
- Longitudinal Industrial Studies – assessment of long-term effects on worker well-being, safety performance, resilience, and operational effectiveness.

Potential performance indicators include accident frequency, near-miss occurrence rates, worker fatigue levels, situational awareness metrics, response times to emerging hazards, organizational resilience, and employee acceptance of intelligent safety technologies.

Future research should also focus on the development of advanced HDT capable of accurately representing worker physiological, cognitive, behavioral, ergonomic, and emotional states in real time. Particular attention should be devoted to fatigue prediction, workload assessment, cognitive overload detection, and worker well-being monitoring.

Another important research direction concerns the advancement of CDT. Future CDT should incorporate explainable reasoning mechanisms, causal inference models, knowledge graphs, foundation models, and generative AI capabilities capable of supporting transparent and trustworthy safety decision-making. Explainable AI will be particularly important in safety-critical environments where recommendations must remain understandable and auditable.

The development of SI as a distinct scientific and engineering discipline represents an additional research challenge. Future studies should investigate methods for transforming operational data into adaptive safety knowledge and establish measurable indicators for evaluating intelligent safety systems.

Ethical, legal, and societal considerations also require further investigation. The continuous collection of worker-related information through HDT raises questions concerning privacy, transparency, informed consent, and data ownership. Similarly, the increasing use of AI introduces challenges related to accountability, explainability, fairness, and trust. Addressing these issues will be essential for achieving broad industrial acceptance of Safety 5.0 technologies.

Another important challenge concerns interoperability and standardization. Future implementation of Safety 5.0 will require standardized communication protocols, data models, and integration frameworks capable of connecting HDT, CDT, AI platforms, IIoT infrastructures, and enterprise information systems within unified socio-cyber-physical environments.

Ultimately, future research should focus on the realization of fully integrated C-CPSS capable of supporting adaptive risk management, resilient Human–AI Collaboration, continuous learning, and autonomous safety interventions. The long-term vision of Safety 5.0 is the creation of intelligent socio-cyber-physical environments in which human intelligence and artificial intelligence continuously cooperate to enhance worker safety, organizational resilience, sustainability, and overall industrial performance.

Achieving this vision will require interdisciplinary collaboration among experts in occupational safety, manufacturing systems, artificial intelligence, digital twins, human factors engineering, ergonomics, cybersecurity, and organizational sciences. Through such efforts, Safety 5.0 may evolve from a conceptual framework into a practical foundation for the next generation of occupational safety management systems.

6. CONCLUSION

The evolution of manufacturing systems from mechanization and automation toward digitalization, cybernation, and cognitization has been accompanied by a corresponding transformation of occupational safety and health management. While Industry 4.0 technologies have significantly advanced connectivity, monitoring, and predictive capabilities, they remain limited in supporting contextual understanding, adaptive reasoning, organizational learning, and effective Human–AI collaboration within increasingly complex socio-cyber-physical environments.

Building on this technological evolution, this study introduced Safety 5.0 as a human-centric cognitive safety paradigm founded on the transition from CPPS to Cognitive Cyber-Physical Production Systems (C-CPPS). Safety 5.0 extends conventional predictive safety by integrating

human intelligence, artificial intelligence, Human Digital Twins (HDT), Cognitive Digital Twins (CDT), and Safety Intelligence (SI) to enable context-aware, adaptive, explainable, and continuously learning safety management.

The main contribution of the study is the proposed Human-Centric Cognitive Safety Framework, which provides a coherent architecture for integrating these concepts within a unified socio-cyber-physical safety ecosystem. Within the framework, HDT support worker-centered awareness, CDT provide contextual interpretation and reasoning, AI enables predictive and adaptive analytical capabilities, and SI transforms contextual knowledge into adaptive safety actions. Human–AI Collaboration serves as the central decision-making mechanism, combining computational capabilities with human expertise, situational awareness, ethical judgment, and final decision authority. The framework is further operationalized through Cognitive Cyber-Physical Safety Systems (C-CPSS), which represent the technological realization of Safety 5.0 in future industrial environments.

This transition from predictive toward cognitive safety also reflects the broader principles of Industry 5.0, particularly human-centricity, resilience, sustainability, and responsible technological development. Rather than treating workers primarily as sources of risk, Safety 5.0 positions them as active cognitive partners whose knowledge and adaptive capabilities complement artificial intelligence. In this way, intelligent safety technologies can support proactive risk management, improved worker well-being, organizational resilience, and continuous learning without replacing human oversight.

The proposed framework should be understood as a conceptual and architectural model rather than a fully validated implementation methodology. Its practical effectiveness and scalability therefore require further validation through laboratory experiments, industrial pilot studies, and real-world applications. Future research should also address the development of advanced HDT and CDT, measurable indicators of Safety Intelligence and Human–AI Collaboration, explainable AI, interoperability, cybersecurity, data governance, and related ethical and regulatory challenges. Overall, the proposed Safety 5.0 paradigm provides a structured pathway toward adaptive, explainable, resilient, and human-centered occupational safety systems for next-generation industrial environments.

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Original scientific paper

OCCUPATIONAL ACCIDENTS IN THE EUROPEAN UNION, 2013-2023: TRENDS, DIFFERENCES IN REPORTING SYSTEMS AND THE CASES OF PORTUGAL AND CROATIA

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Abstract: *Occupational accidents remain a persistent public-health and economic burden across the European Union, despite four decades of harmonised safety legislation. This paper presents a retrospective analysis (2013-2023) of occupational accident statistics in the EU, drawing on Eurostat's European Statistics on Accidents at Work (ESAW) and national data sources, with particular focus on Portugal and Croatia. Findings show that, following a sharp long-term decline that had taken place mostly before 2010, progress has since stagnated, interrupted only by the COVID-19 pandemic. Cross-country comparison reveals substantial divergence driven largely by differences in reporting and recognition systems: Portugal records among the EU's highest non-fatal incidence rates under an insurance-based system despite a marked decline in fatal accidents, while Croatia's low self-reported rates and distinct ESAW transmission practices complicate direct comparison. Construction, transport and agriculture remain disproportionately represented in fatal accidents. The economic burden of work-related accidents and ill-health is estimated at approximately 3.3% of EU GDP, reinforcing the case for renewed, sector-targeted prevention investment.*

Keywords: *Occupational accidents; Occupational safety and health; European Union; ESAW; Portugal; Croatia.*

1. INTRODUCTION

Occupational safety and health (OSH) have been a central pillar of European social policy since the 1989 Framework Directive established the principle that employers must ensure workers' health and safety in all aspects of work [1]. More than three decades later, occupational accidents continue to cause substantial human and economic harm across the EU: in 2023 alone, 3,298 workers died and 2.82 million non-fatal accidents at work were recorded [2]. The European Commission's OSH strategic framework for 2021-2027 explicitly identifies the improvement of accident prevention as one of its three major challenges, alongside adapting to new forms of work and increasing preparedness for health crises [3].

Comparing occupational accident rates across EU Member States is a long-standing analytical challenge. Countries differ not only in underlying occupational risk exposure, shaped by economic structure, sector composition and demographics, but also in how accidents are reported, recognised and compensated, which can materially distort cross-country comparisons [2]. These methodological caveats are particularly salient for two countries that anchor the present analysis: Portugal, which combines an insurance-based reporting system with persistently elevated non-fatal incidence rates, and Croatia, whose self-reported accident rates are among the lowest in the EU and whose national data transmission practices diverge from standard ESAW methodology [4].

This paper presents a retrospective (2013-2023) analysis of occupational accident trends in the European Union, combining EU-wide aggregate statistics with country-level analysis of Portugal, Croatia and a broader set of EU Member States. The objective is threefold: to characterise the evolution of fatal and non-fatal accident rates in the EU over this period; to examine the extent and sources of cross-country divergence, with particular attention to Portugal and Croatia; and to situate these findings within the wider economic and regulatory context of European occupational safety policy.

2. DATA SOURCES AND METHODOLOGY

The analysis is based on secondary statistical data and combines longitudinal trend analysis with descriptive and comparative analysis. The reference period is 2013-2023, covering the most recent decade for which relevant data are available across the principal sources used in this analysis. The dataset combines the Eurostat European Statistics on Accidents at Work (ESAW) database, the EU's principal harmonised source for occupational accident indicators, with national administrative time series for Portugal and complementary EU Labour Force Survey (EU-LFS) data on self-reported accidents, described below. Descriptive analysis characterises the evolution of fatal and non-fatal accident indicators over 2013-2023, while comparative analysis contrasts Portugal, Croatia and a wider set of EU Member States at fixed points in time, principally 2023, the most recent year for which full ESAW data are available.

The analysis draws primarily on the European Statistics on Accidents at Work (ESAW), the main EU data source for occupational accident statistics, established by Eurostat in 1990 and placed on a binding legal footing by Regulation (EC) No 1338/2008 and Commission Regulation (EU) No 349/2011 [5, 6]. Under ESAW methodology, a non-fatal accident at work is an occurrence during the course of work causing physical or mental harm that results in at least four calendar days of absence from work; a fatal accident is one causing death within one year of occurrence [2]. Indicators are expressed as absolute counts, incidence rates (accidents per 100,000 employed people) and standardised incidence rates, the latter adjusting for the differing sectoral composition of national economies through a fixed set of EU activity weights, restricting coverage to NACE Rev. 2 Sections A and C-N [2].

National-level data for Portugal are drawn from the Gabinete de Estrategia e Planeamento (GEP) of the Ministry of Labour, as compiled by Pordata/Fundacao Francisco Manuel dos Santos, providing a continuous time series from 1985 to 2023 [7, 8]. Data for Croatia and other Member States are drawn from Eurostat's ESAW database and complemented by the EU Labour Force Survey (EU-LFS) ad hoc module on self-reported accidents at work [9].

Comparability across countries is affected by two well-documented sources of bias. First, under-coverage and under-reporting vary substantially depending on whether a country's system is insurance-based (offering financial compensation and consequently stronger incentives to report) or based on a general legal obligation; a EUROGIP analysis estimates non-fatal accidents may be under-reported by a factor of two or more in several EU countries relative to a theoretical reference level [4]. Second, national practice in the transmission of ESAW variables is not fully uniform: Croatia, together with France and Italy, transmits accidents of medical or natural origin that other countries exclude, while France's notification system does not always distinguish accidents where work is the principal cause from accidents merely occurring at work, inflating its reported incidence relative to comparable countries [2, 4]. These caveats are considered throughout the analysis, particularly in Section 4.

3. EU TRENDS, 2013-2023

Across the EU, occupational accident rates fell substantially in the two decades preceding this study's window: between 1998 and 2019, non-fatal accidents declined by 58% and fatal accidents by 57% [10]. However, as EU-OSHA noted on presenting these findings, most of this decrease took place before 2010, with numbers stagnating in more recent years [10]. This plateau is visible in the 2013-2023 window covered by current ESAW releases: the non-fatal incidence rate fell only from 1,686 to 1,393 accidents per 100,000 employed people (-17.4%), while the number of fatal accidents was unchanged between 2013 and 2019, at 3,408 [2, 11]. The COVID-19 pandemic interrupted this plateau, with non-fatal accidents falling 12.7% in 2020 as economic activity contracted, followed by a partial rebound of 5.5% in 2021 and further growth in 2022, before falling again by 5.0% in 2023 to 2.82 million; fatal accidents followed a comparable pattern, falling to 3,358 in 2020, rising to 3,389 in 2021, dropping to 3,286 in 2022 and rising slightly to 3,298 in 2023 [2, 11-13]. In 2023 this corresponds to 1.63 fatal and 1,393 non-fatal accidents per 100,000 employed people across the EU (standardised: 2.07 and 1,500, respectively) [2].

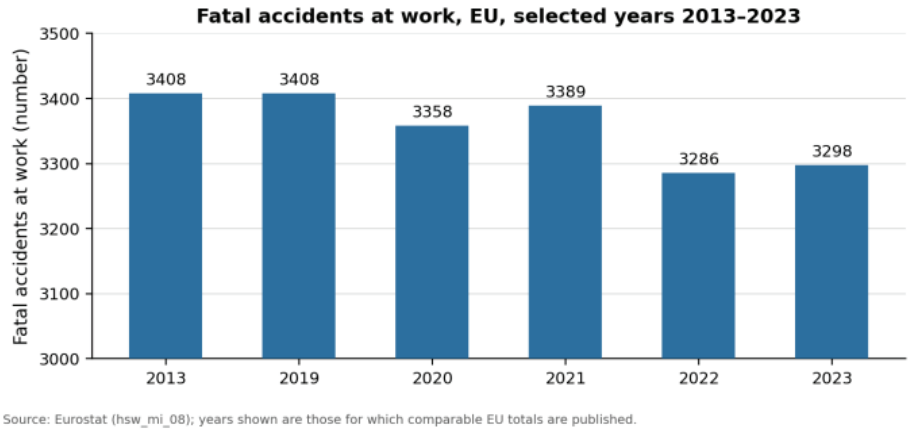


Figure 1: Fatal accidents at work, EU, selected years 2013-2023. Source: Eurostat (hsw_mi_08) [2, 11-13].

The distribution of accidents remains strongly concentrated by sector and demographic group. Construction, transportation and storage, manufacturing, and agriculture together accounted for 66.8% of all fatal accidents in the EU in 2023, with construction alone responsible for 24.0%; mining and quarrying recorded the highest fatal incidence rate of any sector, at

10.8 per 100,000 employed people [14]. A recent sector-specific analysis marking 30 years of the EU's Construction Sites Directive (92/57/EEC) attributes this persistent concentration to recurring gaps in project-stage safety coordination and to the sector's slow adaptation to new working methods, including its transition towards Construction 4.0 [19]. Men accounted for 67.6% of non-fatal accidents in 2023, reflecting the concentration of male employment in higher-risk sectors [2]. Wounds and superficial injuries (29.2%), dislocations, sprains and strains (26.8%), and concussions and internal injuries (20.2%) together accounted for more than three-quarters of all accidents [15].

The economic dimension of this burden is substantial. EU-OSHA and the International Labour Organization estimate that work-related accidents and ill-health cost the EU approximately €476 billion annually, equivalent to 3.3% of EU GDP [16]. A five-country bottom-up costing study found the economic burden of work injuries and diseases ranged from 2.9% of GDP in Finland to 10.2% in Poland, with indirect productivity losses, rather than direct healthcare costs, being the largest cost component in almost every case, and workers and their families bearing the largest share of costs in every country studied [17].

4. COUNTRY DIVERGENCE: PORTUGAL AND CROATIA IN CONTEXT

4.1. Portugal

Portugal's national statistics, compiled by GEP and its predecessor agencies, show a marked decline in the fatal accident rate over 2013-2023: from 3.9 per 100,000 employed people in 2013 to 2.7 in 2023, a reduction of 31%, with a low point of 2.2 recorded in 2018-2019 before a partial pandemic-era increase to 2.8 in 2020-2021 [8]. The total accident rate, reported under Portugal's broader national methodology, which also includes minor cases beyond ESAW's 4-day threshold, declined more modestly, from 4,724.7 per 100,000 in 2013 to 3,654.7 in 2023 (-22.6%), with a peak of 4,788.4 recorded in 2015 [8]. In 2023, 184,607 accidents at work were registered nationally, causing the loss of 5.1 million working days, up from 4.9 million in 2022 despite a slight fall in fatalities, indicating rising severity per non-fatal case [7].

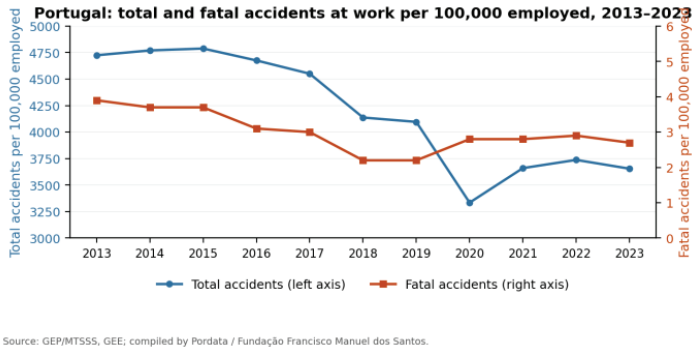


Figure 2: Portugal: total and fatal accidents at work per 100,000 employed, 2013-2023. Source: GEP/GEE, compiled by Pordata [8].

At the same time, under Eurostat's ESAW standardised methodology, Portugal reported the EU's highest non-fatal incidence rate in 2023, at 2,956 per 100,000 employed people, ahead of Spain (2,708) and France (2,644) [2]. Eurostat attributes such elevated rates in insurance-based systems, which include Portugal, Spain and France, to stronger financial incentives for workers to report accidents, in contrast to legal-obligation systems common in eastern and Baltic Member States, several of which report incidence rates below 100 per 100,000, plausibly reflecting substantial under-reporting rather than genuinely safer workplaces [2]. Portugal's case therefore illustrates a broader methodological lesson: a country can simultaneously show a strongly improving fatal-accident trend and a persistently high non-fatal incidence rate, once reporting-system effects are considered.

4.2. Croatia

Croatia presents a more complex profile than a simple under-reporting label suggests. Its ESAW incidence rate (717 non-fatal accidents per 100,000 employed people in 2019, falling to 552 in 2020) sits well below the EU average. EUROGIP's ratio-based method, which compares each country's non-fatal-to-fatal accident ratio (33 fatal and 8,334 non-fatal accidents recorded in 2019) against a theoretical EU reference ratio, estimates Croatia's reporting level at just 18% in 2019, 12% in 2020 and 14% in 2021, among the lowest of all countries assessed [4]. Yet EUROGIP's alternative survey-based method, comparing ESAW records with EU-LFS self-reported data, produces a reporting level of 111% for 2019-2020, implying Croatian statistics are broadly in line with, or slightly above, what households self-report, a divergence EUROGIP itself flags as a methodological limitation rather than a settled finding [4]. More firmly established is that Croatia is one of only three EU countries, together with France and Italy, that transmits accidents of medical or natural origin as part of its ESAW data, and one of the countries most fully including self-employed and family workers in its insured population, both of which limit direct comparability with the EU average [4]. Sectorally, Croatia stands out in transportation and storage: in 2023, 100% of fatal accidents within this sector were attributable to driving or being on board a means of transport, the highest share among the 18 EU countries for which this breakdown is available [14, 15]. Croatia's case illustrates that assessing the completeness of national accident statistics requires triangulating multiple methods, since indicators that appear unambiguous in isolation can be contradicted by other credible sources.

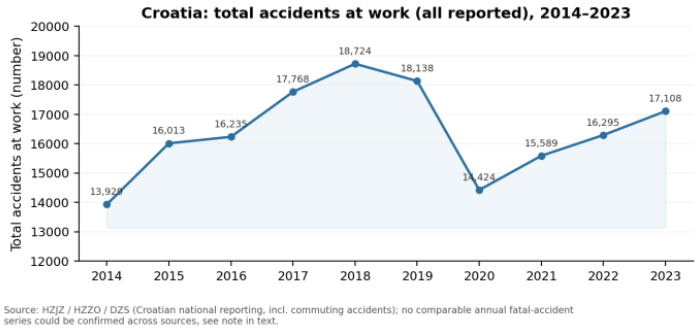


Figure 3: Croatia: total accidents at work under national reporting, 2014-2023. Source: HZJZ/HZZO/DZS [18].

Figure 3 presents the total number of accidents at work reported annually in Croatia under national reporting, rising from 13,929 in 2014 to a pre-pandemic peak of 18,724 in 2018, falling sharply to 14,424 in 2020 and recovering to 17,108 by 2023, a pattern broadly consistent with the EU-wide COVID-19 disruption discussed in Section 3 [18]. Unlike the Portuguese series in Figure 2, this total cannot be reliably paired with a consistent annual fatal-accident count: Croatian national

sources report materially different fatal totals depending on definition (workplace-only versus total, and health-insurance versus labour-inspectorate figures) and, for at least one recent year, disagree with each other by a factor of two [18]. This is itself a further, concrete illustration of the data-quality challenges quantified for Croatia in Table 2.

4.3. Broader country comparison

Beyond Portugal and Croatia, the 2023 country comparison illustrates the scale of EU divergence (Table 1). On a standardised basis, the highest fatal incidence rates were recorded in Cyprus (5.63 per 100,000), Bulgaria (4.50) and France (4.42), while the Netherlands and Germany recorded fewer than 1.00 fatal accidents per 100,000 employed people [2]. France's position is qualified by Eurostat itself, given its distinctive notification system, which does not consistently separate accidents principally caused by work from accidents merely occurring at work [2]. For non-fatal accidents, Slovenia (2,241 per 100,000) and Estonia (957) were the only Baltic or eastern Member States to exceed 700 per 100,000, against Romania and Bulgaria's 58 and 86, respectively, which may indicate substantial under-reporting rather than exceptionally safe conditions [2]. This spread underlines that raw cross-country rankings should not be read as direct safety-performance league tables without accounting for the underlying reporting architecture [4].

Table 1: Selected EU countries: standardised incidence rates, 2023 (per 100,000 employed people)

Country	Fatal	Non-fatal	Reporting system
Portugal	n/a	2,956 (highest)	Insurance-based
France	4.42	2,644	Notification (methodological caveat)
Cyprus	5.63 (highest)	n/a	n/a
Bulgaria	4.50	86 (low)	Legal obligation
Croatia	n/a	n/a	ESAW transmission includes medical-origin cases
Netherlands	<1.00 (lowest)	n/a	n/a
Romania	n/a	58 (lowest)	Legal obligation

Beyond standardised incidence rates, EUROGIP's independent estimates of accident-reporting completeness (Table 2) offer a complementary, and at times contradictory, perspective. Its ratio-based method (comparing each country's non-fatal-to-fatal accident ratio against a theoretical EU reference) and its survey-based method (comparing ESAW records with EU-LFS self-reported data) broadly agree for countries such as France, Germany and the Netherlands, where both methods suggest reporting levels at or close to 100%, but diverge sharply for others: Croatia's ratio-based estimate of 12-18% sits far below its survey-based estimate of 111%, and Portugal's own ratio-based estimate (56-85%) is markedly below the near-universal reporting implied by its high standardised incidence rate in Table 1 [4]. Bulgaria and Romania are the only countries in Table 2 where both methods agree on very low reporting levels, reinforcing that their low standardised incidence rates in Table 1 likely reflect genuine under-reporting rather than exceptionally safe workplaces [4].

A reporting level above 100% under the survey-based method does not imply literal over-reporting: the method benchmarks administrative ESAW counts against EU-LFS self-reported estimates, so a value above 100% simply means that the registered count exceeds what households report in the labour force survey. This can arise from differences in coverage and reference population between the two sources, from recall or self-reporting bias in the survey, or from the inclusion in ESAW of cases that respondents do not themselves classify as accidents at work, rather than from a genuine excess of reported over actual accidents.

Table 2: EUROGIP estimated reporting levels for accidents at work, selected countries (%)

Country	Ratio method (2019/2020/2021)	Survey method (2019-2020)
Germany	100 / 100 / 100	142
Netherlands	100 / 100 / 100	n/a
France	99 / 100 / 100	107
Spain	89 / 63 / 73	135
Portugal	85 / 56 / 58	n/a
Croatia	18 / 12 / 14	111
Romania	1 / 2 / 1	29
Bulgaria	2 / 1 / 1	25

5. DISCUSSION

The 2013-2023 picture that emerges is one of a genuine but stalled decline. The steepest reductions in EU accident rates took place before 2010, reflecting the maturation of the post-1989 regulatory framework and associated improvements in industrial safety practice; the decade examined here shows that this progress has since flattened, interrupted only by the exceptional disruption of the COVID-19 pandemic, suggesting that the most accessible prevention gains have already been achieved and that further reductions will require more targeted intervention in persistently high-risk sectors such as construction, transport and agriculture, which continue to account for two-thirds of all fatal accidents [2, 14]. This pattern is not unique to the EU regulatory context: an eight-year trend analysis of occupational accidents in Turkey identified a comparable persistence of sectoral and demographic concentration despite continuous safety-policy attention, suggesting that structural, rather than purely regulatory, factors constrain further reduction once an initial phase of improvement has been exhausted [20].

The Portuguese and Croatian cases, considered together, demonstrate why single-indicator cross-country comparisons of occupational safety performance are analytically fragile. Portugal's high non-fatal incidence rate under an insurance-based system coexists with one of the EU's more pronounced declines in fatal accidents over the decade, while Croatia's low recorded incidence coexists with sharply contradictory reporting-level estimates and a concentrated, sector-specific fatality risk in transport that is not visible in aggregate national rates. Both cases illustrate the EUROGIP finding that the ratio of non-fatal to fatal accidents, which should approach a theoretical reference level of around 1,422:1 for a fully reporting system, is, in principle, a more robust indicator of under-reporting than raw incidence rates alone, since fatal accidents are far less amenable to non-reporting; yet Croatia's case shows that even this ratio-based method can itself be contradicted by survey-based estimates, so neither should be treated as definitive in isolation [4]. The economic evidence reviewed here, most notably the €476 billion (3.3% of GDP) EU-wide estimate and the wide country-level variation identified for five EU countries (2.9%-10.2% of GDP), further reinforces the case for prevention investment, given that the largest cost component in almost every country studied is lost productivity borne principally by workers themselves rather than by employers or the state [16, 17].

The dual reporting-level estimates in Table 2 add a further layer of nuance with direct policy relevance. Where ratio-based and survey-based methods converge, as for Germany, France and the Netherlands, confidence that reporting is close to complete is reasonably well justified; where they diverge sharply, as for Croatia and, to a lesser extent, Portugal, no single indicator should be

treated as definitive, and national accident statistics are best interpreted as a bounded range rather than a precise figure. This has direct implications for EU-level benchmarking exercises and informal league tables of national OSH performance, which risk systematically penalising countries with more complete reporting systems relative to countries whose comparatively favourable statistics partly reflect substantial, but statistically invisible, under-reporting rather than genuinely safer workplaces.

6. CONCLUSION

This retrospective analysis of 2013-2023 confirms that occupational accidents remain a substantial, only partially resolved challenge for European occupational safety policy. EU-wide fatal and non-fatal accident rates, having fallen sharply in the preceding decade, largely stagnated over the period studied, with construction, transport, manufacturing and agriculture continuing to concentrate the bulk of fatal risk. Portugal and Croatia illustrate, from opposite directions, how strongly national reporting and recognition systems shape observed accident statistics: Portugal's insurance-based system yields comparatively high non-fatal incidence despite genuine improvement in fatal outcomes over the decade, while Croatia's low recorded incidence sits alongside contradictory reporting-level estimates, a distinct ESAW transmission practice and a concentrated transport-sector fatality pattern, none of which is individually decisive.

These findings support four policy priorities: continued harmonisation of accident-reporting methodology across Member States to improve comparability; renewed, sector-targeted prevention investment in construction, transport and agriculture, where the diminishing-returns pattern of the last decade suggests generic measures are no longer sufficient; greater use of the non-fatal-to-fatal accident ratio, alongside raw incidence rates, when benchmarking national OSH performance; and, where ratio-based and survey-based reporting estimates diverge as sharply as they do for Croatia, deliberate triangulation across multiple methods before drawing policy conclusions from any single national indicator. Future research should extend this analysis as post-2023 ESAW data become available, and should further examine the sources of the ratio-survey divergence identified for Croatia and Portugal.

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Review article

THE IMPACT OF ANDRAGOGICAL PRINCIPLES AND WORKER MOTIVATION ON THE EFFECTIVENESS OF TRAINING IN THE FIELD OF OCCUPATIONAL HEALTH AND SAFETY

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Abstract: *This paper analyses the impact of andragogical principles and worker motivation on the effectiveness of occupational health and safety training. Given that worker training involves adults with prior experience, established attitudes, and varying levels of motivation, the paper highlights the need to adapt the training program to workers' actual needs and workplace requirements. The focus is on connecting theoretical content with practical examples, the active involvement of workers in the learning process, and the application of modern training methods that foster understanding, responsibility, and safe behaviour. The paper explores the roles of internal and external motivation in acquiring and applying knowledge in occupational safety. The application of andragogic principles, such as experiential learning, self-direction, practical applicability, and a focus on solving specific problems, can significantly increase worker interest, improve knowledge transfer, and foster a safety culture within the organization. The paper uses a descriptive method, along with the study of available foreign and domestic literature.*

Keywords: *andragogy, worker motivation, occupational safety and health, adult training, safety culture*

1. INTRODUCTION

In the global market competition, it is becoming increasingly difficult to achieve defined goals. The changes that happen daily are such that organizations resort to "*running"* to stay in place. Every *"standing"* threatens to become *"falling behind"*. The development of devices and technology is highly dynamic and involves sophisticated methods of work that are often effective at removing workers from dangerous workplaces and creating safer working conditions. In such an environment, a modern organization must pay more and more attention to developing diverse skills and specialised knowledge among its workers to be able to respond to today's challenges. A growing number of employers are recognizing that their workers' skills and knowledge are valuable resources for enhancing their business competencies. To that end, they organise all the necessary training, both internal and those defined by law. Education comes with numerous challenges at the primary, secondary, and higher education levels. However, the distinctive nature of working with adults is particularly pronounced in the processes of education of workers in the later phase of their lives. The education process should take into account several factors, including the worker's experience, the workplace's needs, the motivation for safe work, and the desire to acquire new knowledge. Individual values and attitudes inherently influence the way workers think and behave in a given work environment. The process of organizational and cultural adjustments for workers in the environment can be problematic from the perspectives of both the worker and the employer. If that process is not effectively led and managed, it can create conditions that contribute to misunderstandings and workplace injuries. Andragogy and its specific approaches can create an environment in which active worker interaction, shared experiences, and practical knowledge establish the prerequisites for improving occupational safety within a work process.

However, the basic prerequisite is the respect of andragogical principles in the creation of worker education programs for occupational health and fire safety. In the paper, some basic andragogical principles and methods will be defined and linked to the quality of workers' occupational safety training. One of the essential prerequisites for the defined education programs to yield appropriate results stems from the assumption that workers are motivated to adopt subject knowledge and that, through the passage of time, new knowledge becomes certain skills that allow the worker to efficiently execute their work duties in a way that will not endanger their life and health. There is a whole set of different facts that influence the acquisition of new knowledge and skills. A lot depends on the engagement of the workers, but also on the readiness of the educator to apply all available knowledge and skills that will allow them to *"entertain"* the workers in the education process. Appropriate training programs provide a solid foundation that can be an effective tool in improving working conditions. Motivated workers show greater interest in acquiring and applying new knowledge, whereas unmotivated workers often do not believe in the educational process, which helps create an environment of disinterest that increases the likelihood of workplace injuries.

This paper will seek to answer questions concerning the connection between training programs, andragogical principles and methods, workers' motivation to acquire new knowledge, and the creation of a safer, more secure work environment. This paper examines andragogical principles and their impact on workers' motivation to apply occupational safety measures, thereby improving the operational efficiency of business organizations. The paper comprises several connected units. Following the introduction, the paper explores the fundamental concepts of andragogy, presenting its definition and historical development. As previously emphasized, the worker training process involves adult learners, and it is necessary to consider the specifics of adult learning and knowledge acquisition. This section is immediately followed by an examination of basic andragogical principles in education. The subsequent section explains the basic concepts of motivation and lists various

worker motivational factors, as well as the influence of safety culture on the creation of a safe environment. Finally, by recapitulating the above, this paper seeks to connect training quality, working capacity, and worker motivation to create a safe work environment.

2. ANDRAGOGY AND WORKER EDUCATION

The concept of andragogy is closely related to education, but there are also differences. The term education appeared in the 19th century under the influence of German idealistic philosophy (Bildung) and literature (Goethe, Schiller), and it is used to denote a harmoniously formed personality primarily in aesthetic and moral terms. [1]. The ultimate goal of education is to foster skill development alongside knowledge acquisition, creating pathways that maximize each individual's potential and future success. The goal of every educational process is to create opportunities for skill development through the acquisition of defined knowledge, which will, in the future, provide better conditions for each individual's development. As a result of acquired knowledge and skills, certain habits are formed depending on the defined jobs performed. Habits by themselves do not necessarily mean something "*bad*", but unfortunately, practice shows that the concept of habits is often associated with monotony, which then leads to handling daily, regular work activities without proper concentration. This lack of concentration when performing work activities then leads to unsafe behaviour and oftentimes ends with minor or major work injuries. In the general public, education is often associated exclusively with the school education system and the interaction between lecturers and students. As a result of that interaction, prerequisites for acquiring certain knowledge are created. Each individual who acquires certain knowledge contributes to increasing their own potential, but above all, they create the prerequisites for applying that acquired knowledge for themselves. This knowledge needs to exist, but it is not a sufficient condition for improving the potential of an individual or society as a whole. However, education is much more than traditional school education. In today's world, with the rapid development of technology, education is essential for individuals and society to acquire new knowledge and skills. Naturally, this is about the activity that represents both the process and the result. When talking about process, it is an activity that is a permanent category because any *"stalling"* in the education process represents "*falling behind"*, which is in the interest of no one. At the end of a certain stage of a process, a result sends a clear message about whether one is on the right path or whether some of the goals and means of the educational process need to be changed. In the field of occupational safety, the results of education are evident in the number of workplace injuries and lost working hours. While some injuries arise from objective factors that cannot be entirely influenced, this information should still be noted as potential alarms warranting correction. Andragogy, as a term, is related to adult education. The very name stems from Greek: *aner, andros* =grown man, and *agogos*, = guidance, direction. Thus, andragogy could be literally translated as *"guiding adults in learning."*

Throughout the development of human civilisation, there has been a need for adult education, evident in various forms from Greek civilisation, through early capitalism, to modern times, when the concept of andragogy arose.Alexander Kapp was a German pedagogist, known for being the first to use the term *"andragogy"* in 1833, which he used to denote the art and science of adult education. In the following period, the term itself was not readily accepted, and the beginnings of andragogy are related to industrialization and the need to respond to the challenges posed by increasingly complex technical and technological systems. The most famous theorist of modern andragogy is Malcolm Knowles, who developed the theory that adults learn differently from children in the second half of the last century. His opinion was based on several key principles. The first starts from the

assumption that adults want to know why they are learning something. They must see the concrete purpose, which then significantly increases their commitment. From the authors' experience as professors at educational institutions, this commitment and focus are evident among part-time students who study while working. Their striving for self-sufficiency is evident, to a certain extent, in their rich experience of learning and applying knowledge in the work environment. Connecting theory and practice and focusing on something useful, created as an integral part of education, largely motivates this category of students to achieve better results. Driven by their experience, they seek to solve problems that arise as an integral part of work processes, becoming active participants in every educational process whenever the opportunity arises to connect educational content with the problems that need to be solved. Additionally, it is important to emphasise that motivation is crucial in this category of participants in educational processes, and that their internal motivation may be more important than external pressure.

Andragogy, or adult learning theory, assumes that adult learners (typically over 25 years of age) bring prior experience, pragmatic motivations, and a desire for autonomy and relevance to learning [2]. Unlike pedagogy, which represents a more traditional approach to teaching children, andragogy emphasises independent learning based on experience and is aligned with personal and professional goals. [3]. For a long time, educational and learning theorists believed that adulthood limits the ability to acquire new knowledge and skills. At the beginning of the last century, the researcher Thorndike experimentally confirmed the thesis that adults do not lose their ability to learn with age. Examining adults' ability to learn, he developed a well-known diagram showing how these abilities change with age. [4].

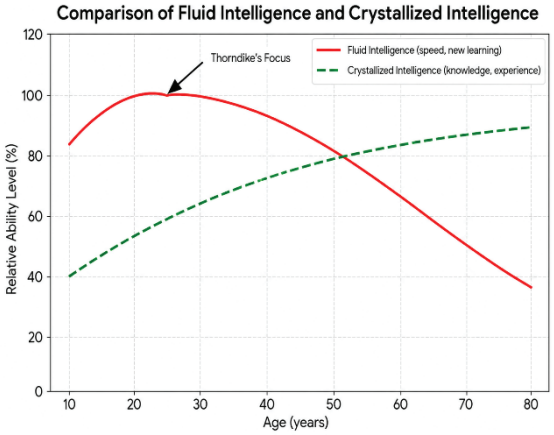


Figure 1: *Thorndike's learning ability curve.*

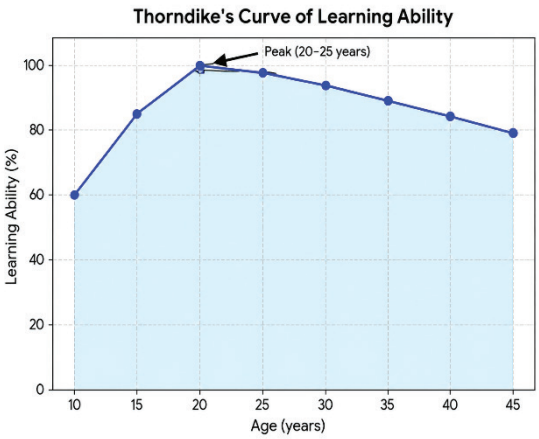


Figure 2: *Comparison of fluid and crystallised intelligence*

The Thorndike curve (Figure 1) shows that learning ability rises sharply until late teens and early twenties. Maximum ability is achieved between the ages of 20 and 25. After 25, the ability declines very slowly, approximately 1% per year. However, even at age 45, a person learns more efficiently than at age 10 or 12. Based on all this, Thorndike concluded that the main enemy of adult learning is not a lack of biological ability, but a lack of motivation, time, or good study habits. On the other hand, the renowned British-American psychologist Raymond Cattell, one of the most influential intelligence and personality researchers of the 20th century, developed the concepts of fluid and crystallised intelligence. While Thorndike saw a general learning ability that peaks in youth and then declines slightly, modern psychology (following Raymond Cattell's model) makes a key distinction between two types of intelligence (Figure 2). Fluid intelligence is closest to what Thorndike measured with his tests. It represents the capacity for logical reasoning, abstract thinking, and the ability to solve emerging workplace problems without relying on prior knowledge. Fluid intelligence reaches its peak in the early twenties and then, due to the brain's biological aging, gradually declines.

Crystallised intelligence represents the accumulated knowledge, vocabulary, experience, and skills acquired throughout a person's life; rather than declining at the age of 25, it continues to grow through middle age and often reaches its peak only in the 60s and 70s [5]. In conclusion, while fluid intelligence may decline slightly after the age of 25, as Thorndike predicted, our *"database"* and the capacity to utilise that data (crystallised intelligence) increase and continue to strengthen. This explains why seasoned professionals are often more efficient at solving complex problems than young beginners.

Educational theory generally defines learning as encompassing planned or unplanned activities, occurring both on and off the job. In many cases, workplace learning in education research has considered the individual's engagement in learning activities for work-related needs and personal motivation. Therefore, all forms of learning– formal, non-formal, and informal learning– are the main focus of education research [6]. For example, Cilasun et al. have defined non-formal learning as "intentional learning that is less organised and less structured" that can occur in the workplace and in the everyday life of any person, while formal learning is "any organised and continuous learning activity that does not exactly fit the above-mentioned definition of formal education"[7]. Furthermore, the development and implementation of state, national, and international workforce development and competency-building policies have become central subjects of educational research [8]. Because adult learning emphasises self-direction, incorporating artificial intelligence into Open Learning Content holds significant potential. Research shows that AI can ameliorate key aspects of adult learning, such as setting goals, finding resources, designing personalised learning plans, monitoring performance, and engaging in reflective practice [9]. In addition, the use of artificial intelligence enables adult learners to receive instant responses, which can help maintain focus and motivation. Lin et al. investigated the use of ChatGPT in asynchronous online discussions and found that AI significantly increased participation and fostered a sense of community among adult online learners. Adult students reported that ChatGPT made discussions more engaging and provided a starting point for deeper critical thinking. This finding shows that AI can act as a catalyst for constructive conversations and the development of transferable skills, including problem-solving, analytical reasoning, and written communication [10]. There are numerous dilemmas regarding the use of modern means in adult education. Certain groups of researchers point to the limitations of artificial intelligence and the lack of consideration of the ethical risks this technology entails. On the other hand, while acknowledging all potential risks, the possibility of improving the quality and efficiency of the educational process through modern solutions is evident.

3. THE CORRELATION BETWEEN ANDRAGOGY AND WORKER MOTIVATION FOR TRAINING

Every adult has a built-in value system that shapes how they think and act regarding workplace safety. Having defined the fundamental concepts of andragogy, the role of andragogy in improving worker and employer competencies is clarified. The next dilemma concerns the limitations and possibilities of contemporary andragogical principles and workers' motivation to acquire new knowledge that will enable them to perform their duties safely and securely. Connecting andragogy and occupational safety represents one of the biggest challenges in corporate education. In the time to come, this area will be particularly interesting. Given the clarity and accessibility of legal regulations and occupational safety bylaws, the frequency and severity of workplace injuries should be significantly lower. Under legal norms, every employer is obligated to prepare a training program for their workers based on a risk assessment of each workplace. During occupational safety training, every worker is introduced to the risks in their workplace and the mandatory measures they must adhere to during work activities, to varying degrees. The employer and the person responsible for occupational safety training must keep this in mind by respecting all modern andragogical principles. Principles represent general notions or guidelines based on which any educational process is organized and implemented. The paper subsequently examines the basic principles, pointing out their advantages and disadvantages [11].

The principle of scientificity requires that the training content be based on proven scientific knowledge, professional facts, and modern work methods. A primary example involves the practical demonstration of the use of personal protective equipment (PPE) for high-risk work at heights, where the risk assessment serves as a critical prerequisite for determining the appropriate personal protective equipment. Another crucial principle asserts that continuous revision, evaluation, and reinforcement of the acquired knowledge is of utmost importance. In accordance with legal norms and internal regulations, employers are obliged to assess their workers' knowledge of occupational safety. The next principle concerns the necessity of connecting theory and practice. If the participants in the education have the opportunity to recognize in the knowledge offered the possibility of solving a problem and to immediately apply that knowledge to their daily work, the education is considered valuable and purposeful. The practical ability of workers to perform certain activities is clearly defined and checked through training programs. Thus, this signifies the possibility and need for workers to demonstrate, through certain activities, whether they have learned something and can apply it. A practical manifestation could be the practical use of a fire extinguisher after theoretical training. The principle of obviousness implies that concrete examples (demonstrations, pictures, models, and practical demonstrations) are used in learning to make the content clearer and easier to understand. If the educational process can create the preconditions for workers to see and feel the machine with their senses (sight, hearing, etc.) and to try using it, then the education imparts practical, applicable knowledge. The basic elements of the system approach are illustrated in the following picture:

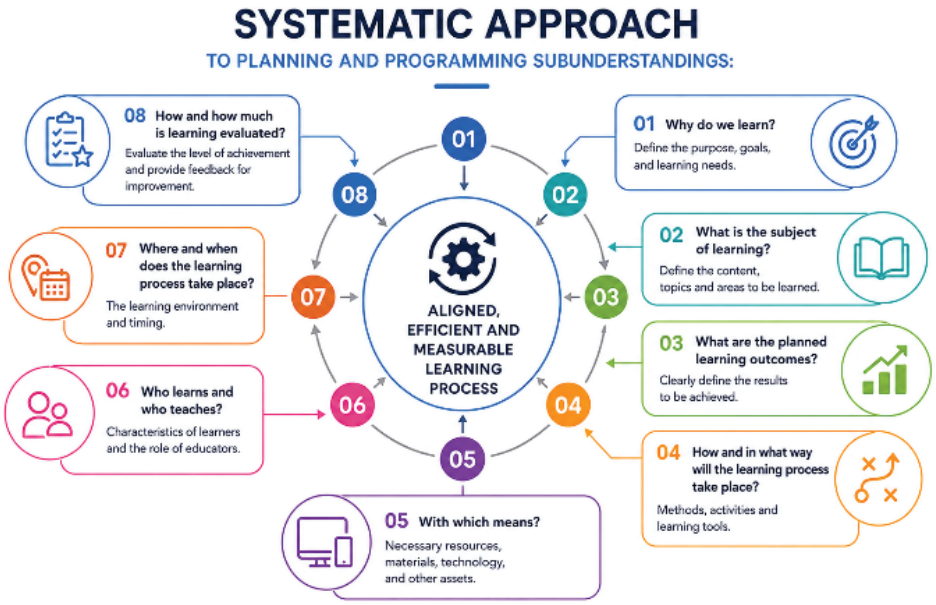


Figure 3: Schematic presentation of a systematic approach to planning and programming in education

However, if the workers lack motivation and an appropriate safety culture, the results of all education and training may be unsatisfactory. The motivation of workers and their willingness to take in new information and knowledge, which should create conditions for a safer workplace, are often a decisive factor in any education. In andragogy, motivation is understood as a set of internal and external incentives that drive an adult to study, improve, and develop personally, thereby increasing their competencies. Adults decide for themselves whether they want to study; their physical presence in an educational setting means nothing if there is no desire to listen, understand, and apply new knowledge in the next phase. According to the authors' experience, workers often evaluate the importance of something based on their frequently superficial knowledge. Depending on that, they decide whether they will be an active listener or a passive observer in an education. Thus, it is important to provide a concrete example of how knowledge is applied and the expected benefits of education. Edward L. Deci was an American psychologist known for his pioneering work on human motivation. Occupational safety psychology examines the comprehensive psychological state individuals develop in specific work environments, shaped by their perceptions of organizational safety culture, managerial support, and their roles. This state includes three basic dimensions: attitudes toward safety, safety-related self-efficacy, and safety-specific emotions. It directly affects individuals' risk assessment and safety decision-making, serving as a foundational cognitive mechanism that leads workers to move from passive compliance to proactive safety actions and practices [12]. At the same time, cognitive psychology holds that the core of human psychology and behaviour lies in cognitive processes. Human behaviour is determined by the interaction between the behavioural environment and the self. Personal behaviour is not an isolated or simple response to external stimuli, nor is it a mechanical sum of many reflex arcs. It is, instead, created by integrating the psychophysical field [13]. Specifically, when workers develop a high level of identification with the project, they internalise safety rules as their own standards of value. This internalisation at a cognitive level significantly improves self-awareness of safety behaviour [14]. Additionally, research shows that self-efficacy in safety psychology directly affects behavioral decisions; that is, the stronger the workers' perception of their own safety capabilities, the more likely they are to proactively avoid risks [15]. Moreover, it has been confirmed that motivation for safety at a cognitive level is the key link that connects

psychological safety and safety behaviour– when workers perceive organizational support, a clear association of the form *"safe behaviour is beneficial"* is created in their cognition, allowing them to spontaneously comply with safety norms without external incentives [16].

The division of motivation into internal (intrinsic) and external (extrinsic) is most commonly associated with the work of psychologists Edward Deci and Richard Ryan [17]. When it comes to internal motivation, it is largely an individual matter. Each person evaluates everything that is integral to their living and working environment differently. In every workplace, workers are exposed to a spectrum of specific hazards that can threaten their lives and health to varying degrees. A person's internal attitude towards workplace challenges can greatly help create a safe environment. When the worker likes something, when something interests them, or when it gives them a sense of personal satisfaction, any education will be much more successful than when they do not have that kind of emotion towards work being done. This type of motivation has long been present in workers' subconscious, and in most cases, it is sustained by their continuous desire for professional growth and expertise. Combined with the gradual shift in their safety culture, these motivational factors are necessary for creating a safe environment. When workers perceive themselves as integral parts of a system and believe their attitudes are essential, this creates important prerequisites for greater creativity, engagement, and dedication in carrying out daily tasks.

Unlike internal motivation, external motivation is always based on external stimuli that represent the basis for worker motivation. When it comes to the spectrum of factors integral to external motivation, punitive measures are the most obvious mechanism. Punishment is an interesting factor that appears to motivate adherence to and respect for defined safety measures at work, and it certainly yields good short-term results. However, as long as the workers themselves lack the awareness and knowledge needed to shift their perspective from obligation (what *must* be done) to a proactive safety mindset (what *should* be done), extrinsic motivation will fail to yield the desired outcomes. In any case, awards and recognition are the preferred method, as they should create a competitive spirit within the collective. The result is manifested not only in reducing the number and severity of workplace injuries but also in changing the safety culture. The purpose of motivation should be workers' desire to train for their own safety, not for raises or to avoid paying fines. In the authors' experience, extrinsic motivation gets workers moving quickly and is great for some short-term goals. However, it only works as long as a threat or reward exists; the moment these incentives are no longer present, motivation disappears as well. Internal motivation arises as a result of one's own desire for improvement, whereas external motivation arises from being guided by the premise of doing something because one is expected to, or must do something.

Motivation is an important factor in creating a safe environment, and there are various ways to increase workers' engagement in their education and daily work. In practice, there are several interesting methods. This paper examines a couple of interesting methods used in the practices of the companies with which the authors collaborate. As a first example, the "*green points*" rule will be defined, and the workers will be introduced to the benefits of this *"game"*. The aim of this method is for every worker who notices any irregularity that can, to a greater or lesser extent, endanger the life or health of workers in the workplace to report it. The report can go to a designated immediate manager or, in more modern organizations with internet platforms, be reported on that platform or on special digital channels created for that purpose. Why should the worker do this? The answer is simple: at the end of the month, all the green points are added up, and the worker who has the most green points gets some kind of reward. This game is a classic example of extrinsic motivation. The prize does not have to be monetary; in fact, it would be better if, in transparent and clear rules, certain free hours, the possibility of purchasing better personal protective equipment, and similar benefits are offered as a prize instead.

Another example activates intrinsic motivation by placing emotional messages in visible places, e.g., "*Someone is waiting for you to come home*." Workers are allowed to hang pictures of family members on the bulletin board, and right next to it, a simple question is pinned: *Who are you wearing protective equipment for?* In this manner, workers' internal motivation can be activated, stimulating them to work safely and securely. By suggesting that photos of loved ones be placed in the lockers, workers' subconscious may be influenced, leading them to be more responsible. It is necessary to foster a culture in the organization where, when someone reports unsafe behaviour, they are not treated as a *"snitch"* of a sort, but rather as someone who helps their coworker return home from work without injuries. Competitive spirit is encouraged among different sectors of a factory (*which is common in some Coca-Cola factories*), in the sense that the section workers who are injury-free for the longest are entitled to some kind of reward (e.g., a joint lunch, paid trips…). In this way, the community spirit is created, and colleagues will look out for each other if they are doing something unsafely. All workers need to be involved in creating a safe environment. An interesting way to do so is to open a "*box for worker suggestions*" (*or a dedicated digital channel*) where suggestions on creating a safer work environment are submitted. At the end of the month, the box is opened, the committee analyses the proposals, and the best solution is awarded and implemented in daily work. This is important because it shows every worker that their opinions are respected.

All of these are solutions that can change workers' perception of their responsibility in creating a safe work environment. Based on all of the above, it is obvious that, through various andragogical principles and methods, conditions should be created to motivate workers to participate in educational processes. Furthermore, these examples illustrate that internal motivation for occupational safety is a much better long-term solution than short-term measures that reflect external motivation. How does one go from external to internal motivation? There are no simple solutions, and greater internal motivation will certainly not come spontaneously. What is necessary is a clear, long-term goal and a path to follow for change to occur. For instance, a worker is wearing personal protective equipment because he is afraid of being punished. How does one change his approach? One solution is to shift the focus to personal gain and try to change his way of thinking through emotional "*manipulation*". Throughout the education, one should not simply read laws and other forms but instead ask the workers for their opinion on, for example, how a possible leg injury would affect their ability to play soccer with their children tomorrow.

In practice, one will encounter long-tenured workers with extensive experience in a certain job. How does one motivate them? One possible answer is to assign these workers the task of analysing near-miss situations, as their knowledge and experience are enormous. This will, in most cases, foster a sense of importance. Additionally, this leads to a strengthening of their *"crystallised intelligence"*, which speaks in favor of the fact that the curve of the possibility of acquiring new knowledge over the years can grow up to 60 years of the worker's life. A series of fire protection trainings, full of interesting video materials, can be organised, but until the worker actually takes the PP device in hand and activates it, that education will most likely not yield the appropriate result. Therefore, it is necessary to insist on a practical presentation of how certain knowledge can be applied, thereby creating the prerequisites for long-term acquisition of knowledge, and workers' motivation to apply this new knowledge.

During the preparation of the risk assessment act, workers should be active participants in the risk assessment for their workplace. Thus, they can identify the hazards present there and offer suggestions on the characteristics of the personal protective equipment they should use. For example, the worker is assigned personal protective equipment– safety glasses, which they should use during work. The safety glasses meet the EN 166 standard. However, wearing those glasses

in certain microclimatic conditions can cause them to fog up, which imposes effort and burden on the worker. Therefore, during the training on wearing them, it is explained that safety glasses with a special coating have been acquired and that, as a result, fogging will no longer occur. A particular dilemma concerns whether it is 1:1 training or group training. Group training is often used in the real sector because it is much more rational in terms of the time needed to train workers. In a certain group, one needs to identify an experienced "leader" and secure their support, as their alignment will ensure that the motivation for applying safety measures is much greater for the whole group.

4. ANDRAGOGICAL PRINCIPLES AND THEIR INFLUENCE ON TRAINING EFFICIENCY

In contemporary times, there is an increasing insistence that all activities involved in creating new value be efficient and rational. The use of modern devices and technology creates prerequisites for increasing productivity on the one hand, and for establishing a safe environment on the other. New devices and technology bring with them new risks, and therefore, it is necessary to organise and implement various education that will help in this mission. Acknowledging the younger generations that are emerging and oftentimes have interesting values and attitudes to life and work, and taking into account the fact that adult education comes with its own unique demands, emphasises the challenges in successfully transferring knowledge through various kinds of education, both mandatory and optional.

Whether teaching people to manage challenging behaviours or improving their communication and professional skills, recognising how adults learn is key to delivering impactful training that resonates[1]. If the right methodology for imparting knowledge is chosen, each group of participants can be motivated to be active participants in the educational process.

Andragogical principles and methods represent a valuable tool that will make the training more interesting, more enticing, and, in this way, enable a faster and easier transfer of knowledge from the lecturer, the person responsible for the occupational safety and health of workers, to the listener. Andragogical principles represent the basic rules and guidelines for adult education, and depending on their clear definition and adaptation to the target group, the educational outcome itself hinges on them.

Their application enables training to be practical, understandable, motivating, and directed towards the participants' real needs, solving their real, not imaginary, problems. In practice, a lot of unnecessary information that is not adapted to the needs of the users of that education can be heard. When workers are unable to connect with the material, which is not relevant to their workplace, they lose motivation to continue active listening and learning. Unlike children, adults enter the learning process with previous experience, developed attitudes, and clear expectations. Because of all this, the training must be designed with the group's characteristics in mind, regardless of their level of education, experience, or age.

As indicators of the possibility of andragogical action on workers, attitudes towards training, job satisfaction, and management satisfaction are singled out [18]. The attitude of workers towards acquiring new knowledge largely determines the quality of the teaching process itself. In simple terms,

[1] https://www.maybo.com.au/thoughtspace/understanding-andragogy-knowing-how-adults-learn-can-enhance-the-effectiveness-of-training/, Accessed on May 2nd, 2026.

if someone has the attitude and opinion that wearing personal protective equipment is unnecessary and burdensome, there is a high probability that their behaviour will reflect that. Workers who have a positive attitude towards education and want to improve themselves are active participants in their education, acquiring knowledge they will apply in the work environment tomorrow. The effects of such an environment over a long period of time inevitably affect the change of the organisational culture itself and ultimately the safety culture as a very important factor in the process of creating a safe environment. Workers' attitudes towards work and the satisfaction they feel while performing it can also largely define their attitudes towards education and training. In most cases, a worker who is satisfied with their job, not only with their salary, has a positive attitude towards improving their knowledge and skills through various education and training. In addition, leadership may be the most significant factor in shaping the workers' relationship towards training. Not so seldomly, the managers who "*do not have time*" for any training are seen in practice. It raises the question of what attitude their workers can have if they see that their immediate managers "*do not believe*" in the need for education and training.

Andragogical principles, most comprehensively defined by Malcolm Knowles, transform training from a passive transmission of information into a process that directly responds to the needs of the adult learner. The application of these principles has a crucial impact on training effectiveness by increasing engagement, knowledge retention, and practical application of what has been learned in the work environment. Knowles discusses six key principles and analyses their impact on the effectiveness of training itself. The first of these principles is student self-direction: adults want to take responsibility for their own learning. When given autonomy in setting goals and choosing methods, their commitment to training increases. The second principle addresses the role of experience and its role in the process of acquiring and applying new knowledge. Adults bring a wealth of personal and professional experience, and effective training uses that experience as a resource (through discussions and case studies), thereby integrating new knowledge more quickly into existing mental maps.[2] The next principle concerns workers' willingness to engage in the education process. The moment workers become aware that training could solve some of their problems, their motivation to learn increases. What is interesting, according to the authors, about andragogical principles is that they focus on placing the focus of education on the problem, rather than the content.

The aim of occupational safety training should be to recognize workplace hazards, define occupational safety measures, and to apply these measures daily. If the content of training becomes overly general and raises imaginary issues that have no direct connection to the potential problem, motivation decreases further and further if the educational process itself lasts a while. Striving to change the organisational and safety culture by shifting the focus from external to internal motivation is of crucial importance for creating a safe environment. Focusing on external motivators yields slightly better short-term results, but internal motivators are a much better long-term solution. In the end, what is, in the authors' opinion, an important question to answer is *"why"* some education is organised. Adults want to understand the underlying reasons for their learning. They engage more deeply when they understand the usefulness of new knowledge and the benefits of applying that knowledge in their daily work. The application of these principles in everyday educational work should create conditions for more participants to complete the training by increasing their motivation.

On the other hand, insisting on practical aspects in education helps create applicable knowledge, which leads to better transfer of that knowledge during education. Finally, at a time when there is a need to increase efficiency and rationality, focusing on essential needs reduces training time and

[2] https://www.maybo.com.au/thoughtspace/understanding-andragogy-knowing-how-adults-learn-can-enhance-the-effectiveness-of-training/ Accessed on May 2nd, 2026.

increases the return on investment in education.[3] As it was previously emphasised, each target group has its own characteristics, which must be taken into account when defining principles and methods for training and imparting new knowledge. In the following table, the focus of each target group is seen:

Table 1: Comparative view of younger and older workers

Target group– younger workers	Target group– older workers
• **The dominance of fluid intelligence** - As younger workers (Gen Z and younger millennials) have high levels of fluid intelligence, they are faster at processing new, abstract information, but lack a knowledge schema where they can place that information • **Training design** - Short formats, intensive problem-solving tasks, working with completely new technologies (e.g., learning a new programming language from scratch) • **Focus** - Innovation and speed of adaptation	• **The dominance of crystallised intelligence** - The cognitive stage is characteristic for adulthood and older age, in which a person primarily relies on accumulated knowledge, experience, and established patterns of thinking, instead of raw speed of information processing • **Training design** - Older workers (Baby Boomers and Gen X) are slower to process new raw data, but excel at connecting new information with existing experience • **Focus** - Relevance and practical application. These workers learn “only what they need” for the job

Most often, solutions are not simple, because it is difficult to organise training in such a way as to form groups of workers in the proposed way. Individual characteristics of each person must also be taken into account. Therefore, in general, for older workers, one should draw on their knowledge, through which they compensate for the potentially slower acquisition of new knowledge. On the other hand, for younger workers, one should provide the structure and context they lack, preventing them from making mistakes stemming from inexperience, despite their quick thinking. When organising training using presentations, one should reduce the amount of information on each slide, as well as the speed of transitions between slides, as this can pose a problem for older participants. Their dilemma must be addressed throughout the whole training, as well as how this new knowledge will make their job easier in the future. If the answer to that question is positive, the worker’s motivation for training will be high.

5. CONCLUSION

Based on everything mentioned above, it can be concluded that andragogy is an extremely important area of modern education, especially in the context of the accelerated development of devices and technology, as well as changes in the labor market. Nowadays, adult education is no longer just a possibility but a necessity for every individual who wants to maintain and improve their professional and personal competencies. Modern approaches to adult learning indicate that experience, motivation, and practical application of the knowledge play a key role in the success of an educational process. Research by numerous authors confirms that adults do not lose their ability to learn, but that the quality and efficiency of knowledge acquisition depend greatly on motivation, the organization of learning, and the connection of theory with practical problems. This is precisely why andragogy highlights independence, experiential learning, and problem-solving as basic principles of adult education. This approach is particularly important in fields such as occupational safety,

[3] The company Rio Tinto Australia has developed the concept of CRM (Critical Risk Management), through which it places a special focus on hazards and harms that can lead to fatal injuries. On a daily basis, workers are reminded of critical risks and this has led to a significant reduction in fatal injuries. Naturally, this does not mean that other dangers and harms are no longer monitored, but rather that the focus has shifted to the “more important” ones that can endanger human life and health.

where the level of knowledge, developed skills, and continuous education directly affect worker safety and the reduction of workplace injuries. Modern technologies and artificial intelligence are further changing the way adults learn, enabling personalised learning, faster access to information, and greater interactivity in the educational process. Although there are certain dilemmas and ethical issues associated with the application of these technologies, their potential in improving the quality and accessibility of adult education is indisputable. In the future, the importance of andragogy will be even more pronounced because a knowledge-based society requires constant improvement and adaptation to new conditions of work and life.

Because of this, it is necessary to develop educational models that will enable adults to continuously acquire nowledge, develop competencies, and actively participate in modern society. Connecting theoretical knowledge with practical examples, demonstrations, and concrete workplace situations is especially important. Adult workers accept new knowledge more readily when they understand its purpose and clearly see the personal benefit of its application. Training must not be limited to formal familiarisation with regulations, but must be aimed at developing workers' awareness, responsibility, and ability to recognise risks and react properly. Successful training must be flexible and adapted to different generations and to the individual characteristics of workers. Finally, it can be concluded that the application of modern andragogic principles is one of the most important preconditions for creating effective, high-quality occupational safety training.

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Original scientific paper

ASSOCIATION BETWEEN SHIFT WORK AND SLEEP QUALITY AMONG CROATIAN NURSES AND NURSING TECHNICIANS

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Abstract: *Shift work has been associated with impaired sleep and adverse health outcomes among healthcare professionals. This cross-sectional study examined the association between shift work and perceived sleep quality among Croatian nurses and nursing technicians. A total of 190 participants (95 shift workers and 95 day workers) completed an online questionnaire including the Pittsburgh Sleep Quality Index (PSQI), the Depression, Anxiety and Stress Scale (DASS), and questions on chronic diseases. Shift workers reported significantly poorer sleep quality than day workers (mean PSQI 8.9 vs. 6.6; p<0.05). Although higher levels of depression, anxiety, and stress were observed among shift workers, these differences were not statistically significant. Likewise, no significant difference was found in the prevalence of chronic diseases. The findings suggest that shift work is associated with poorer perceived sleep quality and support the need for workplace strategies aimed at improving sleep health among nurses and nursing technicians.*

Keywords: *shift work; nurses; sleep quality; occupational health; PSQI*

1. INTRODUCTION

Sleep is a fundamental biological process essential for cognitive performance, emotional regulation, physical recovery, and overall health. Insufficient or disrupted sleep can impair attention, decision-making, work performance, and well-being, while chronic sleep deficiency has been associated with an increased risk of cardiovascular and metabolic disorders as well as mental health problems [1–4]. These consequences are particularly relevant in healthcare settings, where impaired alertness and fatigue may affect both the health of professionals and the safety and quality of patient care. Shift work is an unavoidable feature of modern healthcare because nursing care is provided continuously throughout the day and night. Rotating and night shifts can disrupt circadian rhythms, alter normal sleep–wake patterns, shorten sleep duration, and reduce opportunities for adequate recovery. Nurses and nursing technicians may therefore be especially vulnerable to sleep disturbances because shift work is often combined with high workload, emotional demands, and

responsibility for patient care. Previous studies have consistently reported poorer sleep quality among nurses working shifts or nights compared with those working regular daytime schedules [5–13]. Shift work has also been associated with psychological distress, burnout, depression, anxiety, and a range of adverse physical health outcomes, although findings across studies are not entirely consistent [14–20]. Sleep quality is therefore an important occupational-health indicator in nursing. The Pittsburgh Sleep Quality Index (PSQI) is widely used to assess subjective sleep quality and enables comparison of sleep-related outcomes across different work schedules. At the same time, psychological symptoms and chronic health conditions may coexist with sleep problems and can contribute to the overall burden associated with shift work. Examining these outcomes together may provide a more comprehensive picture of the health consequences of non-standard working schedules among nursing professionals. Despite the substantial international literature on shift work and health, evidence focusing specifically on Croatian nurses and nursing technicians remains limited. Data from the Croatian healthcare context are important because organisational practices, staffing patterns, work schedules, and occupational conditions may influence the relationship between shift work and health outcomes. Therefore, the primary aim of this study was to examine the association between shift work and perceived sleep quality among Croatian nurses and nursing technicians. A secondary aim was to compare symptoms of depression, anxiety, and stress and the prevalence of chronic diseases between shift workers and employees working regular daytime schedules.

2. PARTICIPANTS AND METHODS

A cross-sectional study was conducted among nurses and nursing technicians employed in Croatia between March and April 2025. To obtain two comparable groups, 95 shift workers and 95 day workers were included in the final analysis (N = 190). Participants were recruited using convenience sampling; therefore, the findings should be interpreted with caution and may not be generalisable to all Croatian nurses and nursing technicians. The study included participants of different ages, sexes, educational levels, and years of professional experience. Data were collected using an anonymous online questionnaire consisting of four sections. Sociodemographic data included age, sex, and work schedule (shift work or day work). Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI), a validated instrument evaluating sleep quality during the previous month. Permission to use the questionnaire was obtained from the University of Pittsburgh. Psychological distress was assessed using the Depression, Anxiety and Stress Scale (DASS-42), employing the validated Croatian version. Participants also reported the presence and type of chronic diseases. Shift work (shift vs. day work) was treated as the independent variable. Continuous variables are presented as means and standard deviations, whereas categorical variables are presented as frequencies and percentages. Differences in PSQI and DASS scores between the two groups were analysed using the independent-samples t-test. Differences in the prevalence of chronic diseases were analysed using the Chi-square test. Statistical significance was set at $p < 0.05$. Statistical analyses were performed using Statistica version 12 (TIBCO Software Inc., California, USA). Participation was voluntary and anonymous. Completion of the questionnaire was considered informed consent.

3. RESULTS

Participant characteristics are presented in Table 1.

Table 1: Participant characteristics

Characteristic	Frequency	Percentage	Cumulative frequency	Cumulative percentage
GENDER				
Male	18	9.47	18	9.47
Female	172	90.53	190	100.00
AGE				
18–25	21	11.05	21	11.05
26–35	42	22.11	63	33.16
36–45	55	28.95	118	62.11
46–55	52	27.37	170	89.47
56–65	19	10.00	189	99.47
>65	1	0.53	190	100.00
WORK SCHEDULE				
Shift work	95	50.00	95	50.00
Day work	95	50.00	190	100.00

3.1. Sleep quality

Shift workers demonstrated significantly poorer perceived sleep quality than day workers. The mean PSQI score was 8.9 ± 3.6 among shift workers compared with 6.6 ± 3.6 among day workers, indicating a statistically significant difference between the groups ($p < 0.05$). Descriptive statistics are presented in Table 2.

Table 2: Sleep quality according to work schedule (PSQI scores)

Work schedule	n	Mean ± SD	Median	Range
Shift work	95	8.9 ± 3.6	9	1–20
Day work	95	6.6 ± 3.6	6	0–17

Independent-samples t-test: $p < 0.05$.

3.2. Psychological distress

Shift workers showed higher mean DASS scores than participants working regular daytime schedules (31.2 ± 29.5 vs. 24.2 ± 26.0). However, the difference between the groups was not statistically significant. Detailed descriptive statistics are presented in Table 3.

Table 3: Psychological distress according to work schedule (DASS total score)

Work schedule	n	Mean ± SD	Median	Range
Shift work	95	31.2 ± 29.5	22	0–111
Day work	95	24.2 ± 26.0	15	0–113

Independent-samples t-test: $p > 0.05$.

3.3. Chronic diseases

Overall, chronic diseases were reported by 60.0% of shift workers and 53.7% of day workers. The difference in prevalence was not statistically significant ($\chi^2 = 0.77$, $p = 0.380$). Obesity, asthma, and cardiovascular diseases were the most frequently reported conditions in both groups (Table 4).

Table 4: Prevalence of chronic diseases according to work schedule

Work schedule	Chronic disease n (%)	No chronic disease n (%)
Shift work	57 (60.0)	38 (40.0)
Day work	51 (53.7)	44 (46.3)

Chi-square test: $\chi^2 = 0.77$; $p = 0.380$.

4. DISCUSSION

The present study examined the association between shift work and perceived sleep quality among Croatian nurses and nursing technicians. The findings demonstrated that participants working shifts reported significantly poorer sleep quality than those working regular daytime schedules. In contrast, no statistically significant differences were observed regarding symptoms of depression, anxiety, stress, or the prevalence of chronic diseases.

The observed association between shift work and poorer sleep quality is consistent with previous research. McDowall et al. reported significantly poorer sleep quality among shift-working nurses compared with nurses working regular daytime schedules, even after adjustment for demographic characteristics [9]. Similar findings were reported by Alameri et al. [10], Zhang et al. [11], Mohamud et al. [12], and Huang et al. [13], all of whom found that shift work was associated with poorer subjective sleep quality, shorter sleep duration, and greater sleep disturbances. These findings support the hypothesis that disruption of the circadian rhythm caused by irregular working hours adversely affects sleep quality among healthcare professionals [3–7]. Although shift workers in the present study had higher mean DASS scores, the differences were not statistically significant. This finding differs from several previous studies reporting increased symptoms of depression, anxiety, stress, and burnout among shift-working nurses [14–17]. However, our findings are consistent with those of Özyürek et al. [18], who likewise found no significant differences in psychological outcomes between nurses working day and rotating shifts. These discrepancies may reflect differences in organisational support, workload, coping strategies, sample characteristics, and cultural or healthcare-system factors. No statistically significant association was found between shift work and the prevalence of chronic diseases. Although obesity, asthma, and cardiovascular diseases were the most frequently reported conditions in both groups, their prevalence did not differ significantly according to work schedule. Similar observations regarding cardiovascular outcomes have been reported by Ljevak et al. [19], whereas other authors have demonstrated associations between shift work and gastrointestinal disorders, metabolic disturbances, obesity, and hypertension [20]. The inconsistency of these findings may partly reflect differences in study populations, duration of shift work, and methods used to assess chronic diseases. From an occupational safety perspective, these findings support the consideration of fatigue-management strategies, adequate recovery periods between shifts, and organisational measures aimed at reducing circadian disruption among nursing staff. Several limitations should be acknowledged. First, participants were recruited using convenience sampling, limiting the generalisability of the findings. Second, the cross-sectional design

precludes causal inference. Third, chronic diseases were self-reported rather than confirmed from medical records, introducing the possibility of reporting bias. Finally, the relatively modest sample size may have reduced the statistical power to detect smaller differences in mental health outcomes.

Despite these limitations, the study contributes to the limited evidence regarding the impact of shift work among Croatian nurses and nursing technicians. The use of validated instruments, balanced comparison groups, and the simultaneous assessment of sleep quality, psychological distress, and chronic diseases strengthen the study. Future longitudinal studies are needed to clarify the long-term health consequences of shift work and to evaluate interventions aimed at improving sleep quality and overall well-being among healthcare professionals.

5. CONCLUSION

This study demonstrated that Croatian nurses and nursing technicians working shifts reported significantly poorer perceived sleep quality than those working regular daytime schedules. In contrast, no statistically significant differences were observed in symptoms of depression, anxiety, stress, or the prevalence of chronic diseases. These findings suggest that shift work is associated with impaired sleep quality and highlight the importance of promoting healthy work schedules and sleep hygiene among healthcare professionals. However, given the cross-sectional design of this study, causal relationships cannot be established. Further longitudinal studies involving larger and more representative samples are needed to better understand the long-term health effects of shift work and to evaluate strategies aimed at improving sleep quality and occupational well-being among nurses and nursing technicians.

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Review article

SPECIFIC OCCUPATIONAL HAZARDS IN HOTEL KITCHENS AND EFFECTIVE WORKPLACE SAFETY MEASURES

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Abstract: *Hotel kitchens represent complex working environments characterized by the simultaneous presence of mechanical, thermal, chemical, biological, ergonomic, and psychosocial hazards. Due to the dynamic nature of hotel food service, including continuous meal production, banquet catering, and high work intensity, employees are exposed to an increased risk of occupational injuries and long-term health problems. This paper is based on a narrative review of scientific and professional literature addressing occupational hazards and occupational safety in hotel kitchens. The reviewed literature was analysed to identify the main categories of workplace hazards and the preventive measures most commonly recommended for reducing occupational risks. The findings indicate that occupational injuries in hotel kitchens are primarily associated with the interaction of unsafe working conditions, human factors, and organizational shortcomings rather than isolated hazards. Effective prevention therefore requires an integrated approach that combines employee training, proper equipment maintenance, personal protective equipment, workplace organization, hygiene management, and the development of a strong safety culture. The consistent implementation of these measures contributes to improved employee safety, reduced workplace injuries, and enhanced operational efficiency in hotel kitchen environments.*

Keywords: *Employee training, Hotel kitchens, Occupational risks, Safety measures, Workplace injuries*

1. INTRODUCTION

Hotel kitchens represent one of the most demanding work environments within the hospitality industry due to the simultaneous performance of numerous food preparation activities under strict quality, hygiene, and time requirements. Unlike many other professional kitchens, hotel kitchens often operate continuously throughout the day, serving restaurants, room service, banquets, conferences,

and special events simultaneously [1]. This creates a dynamic working environment characterized by high work intensity, frequent movement of employees, and the simultaneous use of various types of equipment, increasing the likelihood of occupational accidents and health-related risks.

Kitchen employees are regularly exposed to mechanical, thermal, chemical, biological, ergonomic, and psychosocial hazards. The use of sharp cutting tools, high-temperature cooking equipment, electrical appliances, cleaning chemicals, and repetitive manual tasks significantly contributes to the occurrence of workplace injuries and occupational diseases. In addition, prolonged standing, shift work, seasonal workload fluctuations, and constant pressure to maintain service quality may negatively affect workers' physical and mental well-being.

Occupational safety and health therefore represent an essential component of sustainable hotel operations. Effective risk management not only reduces workplace injuries and absenteeism but also improves employee well-being, operational efficiency, food safety, and the overall quality of hospitality services. Consequently, employers should adopt a systematic approach that combines technical, organizational, and educational measures to create a safe working environment.

This paper is based on a narrative literature review of scientific and professional sources addressing occupational hazards and preventive measures in hotel and professional kitchens. The sources were selected according to their relevance to occupational safety and health in the HORECA sector, their focus on kitchen-related hazards, and their practical applicability to workplace prevention measures. Priority was given to more recent literature, while key authoritative sources from occupational safety institutions were also included to support the analysis.

2. BASIC CONCEPTS OF OCCUPATIONAL SAFETY AND THE OCCURRENCE OF ACCIDENTS

Occupational safety includes a set of technical, organizational, and health-related measures aimed at ensuring safe working conditions and preventing injuries and occupational diseases. Its main purpose is to reduce workplace risks to the lowest possible level [2].

Occupational accidents are rarely the result of a single cause; instead, they usually arise from the interaction of human behavior, work equipment, and the working environment. Faulty equipment, unsafe procedures, poor work organization, and inadequate supervision may all contribute to the occurrence of accidents, leading to injuries, material damage, or work interruptions [3].

Occupational diseases develop gradually as a result of long-term exposure to harmful factors such as heat, humidity, chemicals, repetitive tasks, and improper working posture. In hotel kitchens, these risks are particularly relevant because several hazardous factors often occur simultaneously in a fast-paced work environment.

This brief conceptual framework provides the basis for analysing the specific occupational hazards present in hotel kitchens and the preventive measures used to reduce them.

3. RISKS IN HOTEL KITCHENS

Hotel kitchens are complex working environments in which several categories of occupational hazards occur simultaneously. Because food preparation, cleaning, storage, and service activities often take place in a limited space and under time pressure, workers are exposed to a combination of mechanical, thermal, chemical, biological, ergonomic, and psychosocial risks. The significance of these hazards lies not only in their frequency, but also in their cumulative effect on worker safety, health, and overall job performance which distinguishes hotel kitchens from many other food service environments [4].

Mechanical hazards are among the most common risks in hotel kitchens. Sharp knives, slicers, mixers, grinders, and other cutting devices can cause cuts, puncture wounds, crushing injuries, and lacerations. These injuries are often related not only to the equipment itself, but also to fatigue, haste, poor maintenance, and insufficient training. From a safety perspective, mechanical hazards are particularly important because they can lead to both immediate injury and temporary work interruption. [3].

Thermal hazards are an important occupational concern in hotel kitchens, where staff regularly work near ovens, stoves, fryers, steam equipment, and boiling liquids. Exposure to hot surfaces, steam, and splashing liquids increases the risk of burns and scalds, while prolonged work in hot and humid conditions may contribute to heat stress, fatigue, and reduced concentration [5]. In busy kitchen environments, these hazards are often intensified by high work pace, frequent movement, and time pressure, which further increases the likelihood of accidental contact with heat sources [3].

Chemical hazards arise mainly from detergents, disinfectants, degreasers, and other cleaning agents used to maintain hygiene standards. Improper handling, inadequate ventilation, and unsafe storage may result in skin irritation, respiratory symptoms, eye injuries, or chemical burns. Although these hazards may appear less visible than cuts or burns, their importance should not be underestimated, because repeated low-level exposure can also contribute to chronic health problems [5].

Biological hazards are associated with contact with raw food products, food waste, contaminated surfaces, and potentially harmful microorganisms. Poor hygiene practices, cross-contamination, and inadequate temperature control can increase the risk of infection and foodborne illness. In hotel kitchens, biological hazards are important not only from the perspective of food safety, but also because they affect the occupational health of workers who handle contaminated materials on a daily basis [6].

Ergonomic hazards are caused by repetitive movements, prolonged standing, awkward postures, manual handling of loads, and limited recovery time during shifts. These factors may contribute to musculoskeletal pain, fatigue, and long-term disorders affecting the back, neck, shoulders, and upper limbs [7]. Their significance is often underestimated, although they represent one of the main causes of reduced work ability in kitchen personnel.

Psychosocial hazards include time pressure, shift work, staff shortages, high service expectations, interpersonal conflicts, and seasonal fluctuations in workload. These factors may increase stress, reduce concentration, and encourage unsafe work practices. In hotel kitchens, psychosocial hazards are especially relevant because they often intensify other types of risks, such as mechanical injuries or mistakes in chemical handling, by impairing attention and decision-making [8].

Overall, occupational hazards in hotel kitchens should be viewed as interconnected rather than isolated. A single incident is often the result of several contributing factors, such as poor organization, fatigue, inadequate supervision, and insufficient safety culture. For this reason, a critical analysis of kitchen safety must consider both the nature of each hazard and the conditions under which it becomes most dangerous.

4. PREVENTION AND SAFETY MEASURES IN HOTEL KITCHENS

Prevention and safety measures in hotel kitchens should be designed in direct relation to the specific hazards identified in the working environment. Since occupational accidents usually result from the interaction of unsafe conditions, human factors, and organizational shortcomings, effective prevention must combine technical, organizational, and behavioural measures rather than rely on a single control strategy [5].

At the technical level, preventive measures include proper maintenance of equipment, safe workplace design, adequate lighting, non-slip floors, and the use of guarded or well-maintained appliances. These controls are particularly important for reducing mechanical, thermal, and slip-related injuries.

At the organizational level, employers should ensure sufficient staffing, clear task allocation, effective communication, and realistic work schedules. Such measures are essential for reducing time pressure, fatigue, and psychosocial strain, which can otherwise increase the likelihood of unsafe behaviour and mistakes [9, 10].

Education and training remain central preventive measures. Kitchen staff should be trained in safe equipment handling, chemical use, food hygiene, emergency procedures, and recognition of workplace hazards. Regular refresher training strengthens safety awareness and supports consistent compliance with established procedures [11].

Personal protective equipment should be used as an additional protective layer, not as the primary control measure. Non-slip footwear, protective clothing, and cut-resistant or heat-resistant gloves can reduce injury severity, but their effectiveness depends on proper work organization and consistent use [10].

Finally, first-aid preparedness and incident reporting are important elements of workplace safety management. Training employees to respond appropriately to cuts, burns, bleeding, sprains, and other common injuries can reduce the consequences of accidents and improve the overall safety culture.

5. CONCLUSION

Hotel kitchens represent complex working environments in which employees are simultaneously exposed to mechanical, thermal, chemical, biological, ergonomic, and psychosocial hazards. The combined influence of sharp tools, hot surfaces, cleaning agents, repetitive work, time pressure, and insufficient organizational support significantly increases the likelihood of occupational injuries and long-term health problems.

The analysis demonstrates that the most important risks in hotel kitchens do not arise from a single factor, but from the interaction of working conditions, human behaviour, and organizational shortcomings. For this reason, occupational safety must be understood as a systematic process that connects hazard identification, risk assessment, and targeted preventive action.

A clear understanding of the specific hazard categories in hotel kitchens is essential for designing targeted preventive measures and improving workplace safety culture. Effective risk reduction depends on the consistent implementation of technical, organizational, and educational measures, supported by proper equipment maintenance, workplace organization, staff training, and the responsible use of personal protective equipment.

Although risks in hotel kitchens cannot be completely eliminated, their impact can be significantly reduced through coordinated and continuous preventive efforts. Therefore, occupational safety should be viewed not only as a legal requirement, but also as an essential element of employee well-being, operational efficiency, and the overall quality and sustainability of service in the hospitality sector. Future research should focus on evaluating the effectiveness of specific occupational safety interventions in hotel kitchens and identifying strategies for reducing emerging ergonomic and psychosocial risks.

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Professional paper

DIGITAL ADR DOCUMENTATION AND THE ROLE OF THE SAFETY ADVISER

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Abstract: *In 2026, the transport industry is rapidly moving towards digitalized processes, although paper documents remain widely used in practice. The theme of this paper is the application of ADR Chapter 5.4 to electronic transport documentation and its interaction with the e-CMR protocol and the evolving EU regulatory framework, with particular attention to the Croatian context. The main question is how the safety adviser can control data accuracy when documents are generated automatically, whereby the focus of the work shifts to the supervision of the company's information system itself. The paper also discusses experiences and potential practices from neighboring countries regarding roadside inspections and proposes practical solutions for periods without network connectivity or in the event of device failure. The objective of this paper is to demonstrate how properly implemented digitalization, under the oversight of the safety adviser, can enhance transport safety, improve data availability, and support a faster response by emergency services.*

Keywords: *safety adviser, digital documentation, information system, data accuracy*

1. INTRODUCTION

During 2026, the logistics and transport sector is undergoing the most intense phase of digital transformation in history. The logistics and transport sector is undergoing a significant phase of digital transformation. While paper documents have for decades formed the basis of legal and operational security in the road transport of goods, pressure from the European Union towards a sustainable and technologically advanced economy has mandated a complete migration to digital business operations. A key pioneer in this digital shift for road transport is the e-CMR protocol, which sets global standards for electronic consignment notes [1]. One of the important elements of this digital transformation in road transport is the e-CMR, which enables the electronic exchange of consignment note information [1].

This process has not bypassed the most critical segment of transport – the carriage of dangerous goods, regulated by the Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) [2]. A special focus in this transition is placed on Chapter 5.4 of the ADR, which prescribes documentation requirements in detail.

To evaluate this transition, this paper applies a combination of methods: a comparative analysis of current legislative frameworks (comparing Croatian national regulations with EU directives like eFTI), a literature review of relevant regulatory and technical standards, and a case study evaluation of roadside inspection methodologies implemented in neighboring countries (Slovenia, Austria, and Hungary).

The application of Chapter 5.4 of the ADR in a digital format presents both a legal and technological challenge. The application of Chapter 5.4 of the ADR through electronic data processing presents both regulatory and technological challenges, particularly regarding data availability, evidential value, and access during transport, where electronic data must provide evidential value and availability during transport at least equivalent to paper documentation [3]. Traditionally, the transport document (consignment note with ADR data) had to be physically located in the vehicle cabin to be accessible to the driver, inspection bodies, and emergency services. The digitalization of this document requires that the electronic record carries the same, if not greater, legal validity, and that it guarantees data authenticity at any moment of the transport. Digitalization therefore requires electronic transport information to provide evidential value and availability during transport at least equivalent to that required for paper documentation [3], while ensuring data integrity and accessibility throughout the transport operation. The key driver of this change at the European Union level is the Electronic Freight Transport Information (eFTI) Regulation, which obligates Member States to accept regulatory information in electronic format [3].

By connecting e-CMR and the requirements of Chapter 5.4 of the ADR, a unified digital ecosystem is created in which the transport document becomes a dynamic digital object.

Despite these advanced European initiatives, the current legislative framework in the Republic of Croatia has not yet fully adapted to the possibilities offered by digital ADR documentation. The Croatian legal framework is still undergoing the transition towards fully digital dangerous-goods transport documentation; at the same time, recent Croatian legislation already provides for electronic documents and permits required transport documents to be available in electronic form where permitted [4]. While European guidelines allow and encourage digital formats, national practice on the roads often depends on the interpretation of an individual inspector. Therefore, the aim of this paper is to analyze how this legal discrepancy can be bridged through the implementation of advanced information systems, and how the Dangerous Goods Safety Adviser (DGSA) assumes a key role in the transition from auditing paper to auditing the company's software architecture. The transition to fully digital ADR documentation therefore depends not only on the technical capabilities of the system, but also on the applicable legal framework and its implementation.

2. TECHNICAL REQUIREMENTS

2.1. Technical architecture and computer networks for e-ADR systems

For a digital transport document to function in practice according to Chapter 5.4 of the ADR, a company's information system must be built upon a stable, fast, and highly available network architecture. The system must not be viewed as an isolated application, but rather as a distributed network ecosystem that connects the consignor, carrier, driver, consignee, and state authorities in real time.

The foundation of this architecture consists of a hybrid cloud model (Hybrid Cloud - a computing environment combining on-premises infrastructure with public cloud services). Sensitive business and client data can be kept on local, on-premises servers, while operational data required for transport is replicated to highly available public clouds (such as AWS or Microsoft Azure) to ensure that the driver and inspection applications are available 24/7. Communication between these components takes place via standardized Application Programming Interfaces (APIs – software interfaces that allow different applications to communicate), primarily utilizing secure RESTful services that exchange data in structured formats such as JSON (JavaScript Object Notation – a lightweight data-interchange format) or XML (Extensible Markup Language – a markup language that defines rules for encoding documents).

At the operational level, data transmission to and from the vehicle relies on modern mobile telecommunication networks (4G and 5G). Vehicles carrying dangerous goods are increasingly equipped with IoT (Internet of Things – a network of physical objects embedded with sensors and software for connecting and exchanging data) devices and telematics systems. Through M2M (Machine-to-Machine) communication, these devices continuously transmit vehicle location data (GPS), as well as cargo status indicators (e.g., temperature inside the tank, pressure, valve-opening sensors). All of this telemetric data is automatically linked to the unique identifier of the digital ADR document.

Network resilience is a critical safety factor. Since trucks traverse geographical areas with varying signal quality (tunnels, mountain passes, border zones), the computer networks within the e-ADR system must utilize techniques like dynamic routing and data packet optimization to minimize bandwidth consumption and ensure that the document status updates as soon as even the weakest network signal is established. The network infrastructure must feature built-in, full redundancy – if the primary telecommunications operator fails, the vehicle's onboard system must automatically switch traffic to a secondary network or a satellite link (such as Starlink in more advanced fleets) to keep the continuity of supervision uninterrupted.

2.2. Cybersecurity and database protection

The digitalization of dangerous goods transport introduces serious security risks in the form of cyber threats. Data regarding the transport of substances such as explosives, toxic gases, flammable liquids, or radioactive materials is no longer merely logistical data; it becomes a target of interest for malicious actors, terrorist groups, or competitive espionage organizations [5]. Intercepting this data could allow the precise localization of high-risk cargo for the purpose of sabotage or theft. Therefore, an e-ADR system must be classified as part of a company’s critical information infrastructure.

The core of the system's defense is centered on database security. Databases (whether relational, such as PostgreSQL or SQL Server, or non-relational NoSQL databases) that store information on UN numbers, quantities, routes, and packing groups must implement rigorous security mechanisms:

Cryptographic Data Protection (Encryption): Data must be encrypted in two key states:

Data at Rest: All records on server disks are encrypted using the AES-256 (Advanced Encryption Standard with a 256-bit key – a symmetric encryption algorithm widely regarded as military-grade security) standard. Even in the event of the physical theft of hard drives, the data remains unreadable without the proper encryption keys.

Data in Transit: All communication between client devices (drivers' tablets, office computers) and the servers must be protected by the TLS 1.3 (Transport Layer Security version 1.3 – a cryptographic protocol designed to provide communications security over a computer network) protocol, preventing Man-in-the-Middle (MitM) attacks and traffic interception.

Ensuring Data Integrity: To guarantee that no unauthorized person has modified the quantity or type of dangerous goods during transit, cryptographic hashing algorithms (e.g., SHA-256 – Secure Hash Algorithm 256-bit, which generates a unique fixed-size digital fingerprint of data) are applied. When a document is issued, a unique digital fingerprint (hash) is generated. Any subsequent unauthorized change to the document—even the slightest modification—invalidates the hash value, immediately alerting the system. In advanced systems in 2026, a private Blockchain (distributed ledger technology) is used for this purpose, making all e-ADR documents immutable.

Backup Strategy: A strict "3-2-1" backup rule is applied. This requires maintaining at least three copies of the data, stored on two different types of media, with at least one copy located at a remote, geographically dislocated location (off-site / cloud-vault). This off-site copy must be completely isolated from the primary network to prevent Ransomware (malicious extortion software) from encrypting both the primary data and the backups simultaneously.

2.3. Access management (identities and authorization)

One of the fundamental tenets of cybersecurity in transport systems is the implementation of the "Zero Trust" model (Never trust, always verify) [6]. Within this framework, no user or device is automatically trusted, regardless of whether they are located inside the company's local network or accessing it from the outside. Every data access request must be identified, authorized, and validated.

To manage access rights to dangerous goods transport data, a Role-Based Access Control (RBAC – an approach to restricting system access based on a person's role within an organization) model is utilized. Data is segmented so that employees and external stakeholders have access exclusively to the specific information necessary to perform their duties (Principle of Least Privilege).

Table 1. Data Access Rights Matrix (RBAC)

System Role	Data Access Level (Read/ Write/Delete)	Scope of Data Visibility
Dangerous Goods Safety Adviser (DGSA)	Read / Write (*solely for validation and rules*)	Full insight into all technical substance attributes, approved routes, change history, and incidents.
Logstician / Dispatcher	Read / Write	Entering new transports, assigning vehicles and drivers, defining routes.
Vehicle Driver	Read (*Read-only*)	Exclusively data for the order currently being executed (active e-ADR and instructions).
Emergency Services (112)	Read (*authorized access*)	Access to relevant transport information in an emergency, subject to authorization, national implementation, and system availability.
Warehouse Staff / Loaders	Read	Data regarding packaging, hazard labels, and loading schedules (excluding commercial pricing).

WHO MUST NOT HAVE ACCESS TO THE DATA?

Access to the sensitive data within the e-ADR system is strictly prohibited for third parties who are not directly involved in the transport chain. This includes external marketing agencies, unauthorized subcontractors, or lower-ranked administrative personnel within the company itself (e.g., general affairs department, human resources).

Commercial details (commodity prices, profit margins) must be completely segregated from dangerous goods safety data by the software. This architecture ensures that technical personnel cannot view financial data, and financial personnel do not have the ability to modify chemical specifications.

AUTHENTICATION MECHANISMS

All users with data entry or modification privileges (dispatchers, safety advisers) must utilize robust Multi-Factor Authentication (MFA – an authentication method requiring users to provide two or more verification factors to gain access). Access to the system is impossible using only a username and password; it strictly requires a second factor—such as a hardware token, biometric scan (fingerprint, facial recognition), or a one-time passcode (OTP - One-Time Password) generated via an authorized application on an official company smartphone.

2.4. The new role of the dangerous goods safety adviser (DGSA) in automated systems

With the introduction of the e-CMR protocol and automated information systems (such as ERP solutions, SAP, or specialized TMS - Transport Management Systems software), the generation process for transport documents is changing radically. In traditional operations, a dispatcher or warehouse worker manually fills out a paper ADR document, leaving a massive margin for human error (incorrect UN numbers, inaccurate substance names, wrong packing groups, or miscalculated tunnel codes).

In 2026, documents are generated automatically. When the system receives an order, an algorithm pulls data directly from the product Master Data database and automatically creates a digital e-ADR document. In such an environment, the role of the Dangerous Goods Safety Adviser (DGSA) undergoes an evolution: their focus shifts from the physical inspection of individual paperwork to the oversight and auditing of the company's information system itself. The adviser becomes a systems auditor and an algorithmic controller.

The primary task of the adviser is to ensure that the "Business Rules" embedded within the software are accurately programmed in compliance with the current ADR regulations [2]. The adviser must control and regularly validate the following system segments:

Master Data Audit (Accuracy of Master Data): If a UN number or packing group is incorrectly entered in the database for a specific chemical product, the system will generate thousands of faulty documents at lightning speed [2]. The DGSA conducts periodic software audits and locks fields containing ADR data so that no one can modify them without explicit authorization.

Algorithmic Control - Verification of Automated Calculations: The software should be designed and periodically tested to accurately calculate exemption points according to sub-section 1.1.3.6 of the ADR (the so-called "exemptions related to quantities carried per transport unit") [2]. The adviser

tests the algorithm by injecting test orders to verify whether the system correctly identifies when the 1,000-point threshold is exceeded, thereby automatically demanding full ADR equipment and orange plates on the vehicle.

Mixed Loading Prohibitions Management: The system must feature a built-in mixed loading prohibition matrix according to Chapter 7.5.2 of the ADR [2]. The adviser oversees the software scripts, which must automatically block a dispatcher if they attempt to assign Class 1 substances (explosives) to the same truck (or digital order) alongside incompatible substances from other classes. The adviser, therefore, defines the operational logic that governs the software.

2.5. Experiences from neighboring countries and emergency solutions (offline mode)

The implementation of digital ADR in Croatia can benefit greatly from analyzing practices in neighboring European Union countries [7]. Slovenia, Austria, and Hungary have developed advanced roadside inspection methodologies that minimize the need for paperwork.

The Slovenian police and transport inspection, for instance, utilize systems connected to national eFTI access points [8]. When a vehicle is pulled over, the inspector does not physically enter the cabin to retrieve paperwork; instead, they scan a QR code from the driver's tablet or smartphone, or enter the vehicle's license plate number into their terminal [2]. The system pulls the entire e-ADR document from the cloud within seconds, verifying the accuracy of UN numbers, tank approvals, and driver certificates. Experiences from Austria demonstrate that this method reduces inspection times by more than 70%, minimizing delays and increasing traffic throughput.

However, the primary argument raised by critics of digitalization is: What happens when the system fails? What occurs when a vehicle finds itself in a mountain range with no mobile network signal, or when a complete hardware failure occurs? The digital system must provide robust solutions for operating without an internet connection (Offline Mode) and strict emergency protocols.

Offline Mode Technology

The application on the driver's mobile device must not depend on a constant internet connection. During loading and the subsequent generation of the e-CMR/e-ADR document at the warehouse (where a stable Wi-Fi or 4G connection is present), the entire data package—along with its cryptographic digital signature and the generated QR code—is locally stored and encrypted within the device's memory (using a local database such as SQLite – a C-language library that implements a small, fast, self-contained, high-reliability SQL database engine).

If an inspector stops the vehicle in a zero-signal zone, the driver opens the application, which generates the QR code on the screen locally, without requiring internet access. The inspector's device then reads the data directly from the driver's device using short-range technologies (such as Bluetooth, Wi-Fi Direct, or advanced local scanning of a QR code that contains fully compressed textual cargo data). This completely satisfies the legal requirement that the transport document must be accessible within the vehicle at all times.

Device Failure Protocol (Hardware Failure)

In the event that the driver's tablet breaks, overheats, or suffers a battery failure, the company's "Dual-Device" security policy is activated. The system must support simultaneous synchronization across two devices (e.g., an official tablet mounted in the cabin and the driver's personal or secondary official smartphone).

If both devices fail, the dispatch center's emergency operational protocol takes effect: the company's 24/7 dispatch center, upon request by the police or inspectors (who identify themselves using the vehicle's license plate), instantly transmits a secure SMS link, a fax, or utilizes a state telecommunications channel to deliver the cargo data directly to the control authority's device.

2.6. Impact on emergency services and safety enhancement

The ultimate and most critical objective of digitalizing dangerous goods transport—driven by the expert oversight of the Dangerous Goods Safety Adviser—is to dramatically elevate public safety and environmental protection, with a specific focus on optimizing the operations of emergency services (firefighters, emergency medical services, police, and civil protection).

In a traditional paper-based system, during a severe traffic accident (e.g., a tanker overturning on a highway), the documents are frequently trapped inside a destroyed or burning vehicle cabin, or soaked in spilled hazardous chemicals, rendering them completely inaccessible. Firefighters arriving at the scene face a dangerous unknown: they do not know what substance is being transported, its specific hazards (flammability, toxicity, reactivity with water), and must risk their lives approaching the vehicle simply to read the orange plates and hazard labels.

The digital e-ADR system completely eliminates this vulnerability through the concept of "Real-Time Incident Visibility." The moment the 112 Emergency Center receives a report of a commercial vehicle accident, the dispatcher enters the truck's license plate number into the system. Via an integrated national API system connected to the eFTI platform—or directly to the carrier's database—emergency services obtain an exact breakdown of the digital transport document within milliseconds [8]:

Exact Chemical Identification: The precise name and chemical composition of the substance (UN number) are instantly known [2].

Accurate Cargo Volume: The exact quantity of the payload loaded into the vehicle at the time of departure is visible.

Automated Emergency Protocols: The "Instructions in Writing" (according to Chapter 5.4.3 of the ADR) are automatically retrieved [2]. This ensures that the firefighting brigade commander knows exactly which extinguishing agent to use (e.g., specialized foam instead of water) and what evacuation radius to establish while still on their way to the crash site.

3. CONCLUSION

The digitalization of the transport sector in 2026 is not merely an administrative transition from paper to screens; it represents a fundamental shift in the core philosophy of safety and security [9]. The application of Chapter 5.4 of the ADR through e-CMR and eFTI protocols introduces transparency, speed, and an incomparably higher level of oversight [1, 2, 8, 10]. Although the current legislative framework in Croatia still shows some resistance to completely abandoning paper, the technological solutions and practices from neighboring countries prove that the digital ecosystem is mature, secure, and sustainable [11].

The key to the success of this transformation lies in redefining the role of the Dangerous Goods Safety Adviser (DGSA). By shifting their focus from the reactive inspection of paperwork to the proactive oversight of the company's information systems, database architectures, and computer networks, the adviser becomes the ultimate guarantor of both IT and physical safety. Coupled with the implementation of robust cybersecurity defenses—such as advanced encryption [7], the Zero Trust model [6], and offline redundancy—digital ADR ceases to be a legal risk and becomes the most powerful tool for protecting human lives, property, and the environment along modern transport corridors.

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Review article

LADDERS AS WORK EQUIPMENT: TECHNICAL AND SAFETY ASPECT

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Abstract: *This paper outlines safety aspects and technical requirements for safe work at height using ladders. Since ladder falls frequently cause severe occupational injuries, a systematic prevention approach is necessary. The objective is to critically analyze technical requirements, legal frameworks, and practical safety challenges of portable ladders. The methodology comprises a literature review of Croatian legislation, EN 131 standards, and international research. Ladder operations present significant physical and psychological challenges due to static strain and balance maintenance, exhausting concentration and limiting quick reactions. When planning activities, tasks must be selected to ensure stability. Ladders must be stable and fit for purpose, in line with regulations. Finally, integrating risk assessment with correct equipment selection is crucial for protecting workers.*

Keywords: *ladder safety protocols, risk assessment integration, fall prevention strategies, work equipment legislation*

1. INTRODUCTION

In daily practice, within production plants, construction sites, and even office spaces, certain work equipment is treated with particular caution. Forklifts, cranes, circular saws, and high-voltage tools automatically command respect and caution from workers. On the other hand, ladders are too often perceived as a simple, basic, and virtually harmless piece of work equipment. This perception is one of the greatest misconceptions in the field of occupational safety and health.

Statistical data and accident chronicles clearly illustrate reality: falls from ladders are at the very top of the causes of severe occupational injuries and fatalities [1]. According to international data from the European Agency for Safety and Health at Work (EU-OSHA) and the U.S. Bureau of Labor Statistics (BLS), falls from ladders account for over 20% of all occupational fall injuries, representing a major public health and economic burden [2, 3]. Recent ergonomic research highlights that human factors—such as overreaching and improper setup angles—are critical catalysts for these events [4]. Severe occupational injuries rarely occur due to complicated technological processes; they are most frequently the result of underestimated risk, improvisation, lack of worker training, and the use of equipment that is technically defective or lacks a valid certification entirely.

2. TECHNICAL REQUIREMENTS

2.1. Legal regulation in the Republic of Croatia

Occupational safety when using ladders is not a matter of goodwill on the part of the employer, but a strictly defined legal obligation. In the Republic of Croatia, this segment is regulated by several key legal acts:

- Occupational Safety and Health Act (Official Gazette,No.71/14,118/14,154/14,94/18,96/18) [1]:

As the foundational law, in its Article 42, it obligates the employer to design, construct, and maintain workplaces and work equipment. This is critical because it removes the assumption that safety is subjective, placing the absolute baseline of accountability on corporate management. Furthermore, Article 61 explicitly mandates the obligation to conduct testing of work equipment exposed to conditions causing its deterioration.

- Ordinance on Occupational Safety and Health for Workplaces (Official Gazette, No. 105/20) [5]:

This ordinance defines the conditions that workplaces must meet. Its primary importance lies in controlling environmental factors (e.g., surface stability and clear evacuation routes) before the equipment is even deployed.

- Ordinance on Occupational Safety and Health in the Use of Work Equipment (Official Gazette, No. 18/17) [6]:

The most important subordinate piece of legislation regarding this topic. In its Article 11, it regulates in detail the dynamics, conditions, and obligations for performing work equipment inspections, thereby ensuring that the equipment retains its factory-certified safety properties throughout its entire life cycle, minimizing material fatigue risks.

2.2. Practical application of the for workplaces ordinance and spatial setup

When ladders are brought into a workspace, spatial and organizational conditions must be met to neutralize external hazards:

- Stability and strength of the surface [5]:

The surface on which the ladder is placed must be sufficiently firm, level, and stationary. The Ordinance strictly prohibits placing ladders on unstable elements such as pallets, crates, or bricks to gain height. If the surface is soft (e.g., soil on a construction site), it must be mechanically secured by placing firm wooden or metal planks underneath to prevent one leg from sinking.

- Evacuation and transport routes [5]:

Ladders must never be positioned in a way that narrows or blocks routes for evacuation and rescue. If work must be performed in hallways, passageways, or forklift transport routes, the work zone must be physically cordoned off with safety tape, cones, or barriers.

- Working behind closed doors:

If a ladder is placed directly behind doors that open toward the worker, those doors must be locked, or a second worker must be stationed in front of them to prevent sudden opening and the overturning of the ladder.

- Construction excavations and roof access:

A particular safety challenge is using portable ladders to access deep trenches or high roof surfaces. In accordance with construction safety standards and the EN 131 framework, ladders used for entering/exiting an excavation or accessing a roof must extend past the edge of the trench or the roof eave by at least 1 meter. This extension allows the worker to continuously maintain the three points of contact rule during the critical transition phase [7]. For leaning ladders, a proper inclination angle of approximately 75° (a 1:4 ratio) must be maintained to prevent the base from sliding backward or the ladder from flipping over. Models longer than 3 meters must have a wider stabilizer cross-base installed at the bottom, and the top must be mechanically secured to neutralize lateral slipping [8].

2.3. Operational rules and ergonomic restraints

According to this ordinance on the use of work equipment [6], ladders are treated as temporary work equipment for work at height, enforcing strict behavioural boundaries:

- Restriction on use (Annex II, point 4.1.2):

Work at height using ladders may only be performed under conditions where the use of other, safer work equipment (such as scaffolding or elevating platforms) is not justified due to a low level of risk, the short duration of the work, or existing field circumstances [6]. Ladders are primarily work equipment for accessing heights, not a permanent "workplace".

- Ergonomics and three points of contact:

During ascending, descending, and working, the worker must maintain a secure grip and a stable foothold at all times. In practice (two feet and one hand, or two hands and one foot permanently fixed) [4]. Tools must be carried in a tool pouch around the waist, keeping the hands free.

- Prohibition of carrying heavy loads:

The framework explicitly emphasizes that only light work may be performed from a ladder [6]. The worker must not carry loads that compromise stability.

- Weather conditions (Annex II, point 4.1.6):

If ladder operations are conducted outdoors, work must be suspended immediately in the event of unfavourable weather conditions (strong winds, rain, ice) [6].

2.4. Typology and model-specific risks

Not all ladders are equal, and consequently, they do not carry the same risks. The umbrella standard HRN EN 131-1:2019 [8] defines the typology of portable ladders.

Table 1: Technical comparison and primary risks of ladder models

Ladder type	Key technical feature (EN 131)	Primary risk factor	Critical prevention measure
Single ladders	Requires support against a solid structure. Models >3m must have a wide base stabilizer.	Base sliding backward or lateral tipping.	Ensure a 75° inclination angle; secure the top to the structure.
Double (self-supporting / A-frame)	Deploys independently. Must feature safety chains/ straps and rigid hinge locks.	Lateral tipping from sudden movements; structural spreading.	Never stand on the top two rungs; fully engage mechanical hinge locks.
Multi-purpose / articulated	Transforms into various configurations via multi-setting hinge joints.	Hinge mechanism failure or incomplete locking under torsion.	Pre-use verification of joint engagement; avoid overloading.

2.5. Product factory certification procedure

A manufacturer cannot independently declare a ladder safe; they must engage an independent, accredited certification body. In accredited laboratories, a prototype ladder undergoes destructive mechanical testing in accordance with HRN EN 131-2:2011 [9]:

- Strength test: The ladder is loaded with forces exceeding 270 kg. For professional use, the final declared load capacity must be a minimum of 150 kg [9]
- Torsion and bending test: The resistance of the stiles to twisting and the maximum allowable deflection of the side rails under load are tested.
- Foot slip resistance test: Rubber or plastic feet are tested on various surfaces to ensure slip prevention.

In terms of factory practice, these laboratory procedures are strictly standardized, meaning the prototype is sacrificed to prove the model's safety margin. To maintain certificate validity, the manufacturer must undergo an Annual Factory Audit (every 12 months) where the certification body verifies raw material quality according to HRN EN ISO 9001:2015 [10]. If the manufacturer alters the profile thickness or aluminium grade, extraordinary recertification is immediately required.

2.6. Obligations of the employer and field exploitation

When ladders enter a company, the responsibility for maintaining their correct operation transfers to the employer through an inspection system [6].

Employer inspection workflow & checklist:

- Before first use: A qualified person must inspect the equipment to ensure it was not damaged during transport and matches the required safety standard [6].
- Pre-use inspection (by the worker): Done before each shift. A quick visual check: rungs for cracks, cleanliness (free of oil, mud), and presence of rubber feet.
- Periodic inspection (every 12 months): A deep inspection by a qualified person recording geometry, bolt tightness, and material fatigue [6, 11]. Portable ladders with structural damage must not be repaired (by welding or straightening) as this voids the factory certificate and compromises structural integrity.

Equipment is only as safe as the person using it. A worker using a ladder must be medically fit to work at height and previously theoretically and practically trained for safe operation with the work equipment, which includes familiarity with the pictogram instructions in accordance with the standard HRN EN 131-3:2018.

2.7. Critical discussion

A critical review of the literature and field practices reveals several vulnerabilities in current safety systems.

- Most common accidents and high-risk models: Recent international statistics indicate that the most common ladder-related accidents stem from base slipping (leaning ladders) and lateral tip-over due to overreaching (A-frame ladders) [2, 4]. Double (A-frame) ladders present the highest statistical frequency of injuries in commercial environments, primarily because users frequently step onto the top rungs or attempt to move the ladder while standing on it.
- Sufficiency of Croatian regulations: The legislative framework in the Republic of Croatia is robust regarding the allocation of liability, clearly defining that the employer bears full material responsibility [1, 6]. However, it remains largely descriptive and lacks specific technical parameters. For instance, the exact setup angles, precise step-off clearances (the 1-meter rule), and detailed inspection protocols are not explicit in the text of the Ordinances; instead, they rely on the "rules of the profession" and references to European standards. This creates a gap where smaller employers, who may not purchase copy-protected EN standards, operate in a technical vacuum.
- EN 131 vs. OSHA Recommendations: Comparing European and American practices highlights distinct methodological approaches. While the European EN 131 standard heavily emphasizes structural modifications—such as mandating base stabilizers for all leaning ladders over 3 metres [8]—the American OSHA (29 CFR 1910.23) framework places greater weight on strict operational metrics and user-focused constraints, such as explicit load-tier classifications (Type IAA, Type IA, etc.) based on exact working weights [12]. Incorporating OSHA's explicit weight-category training into European risk assessments could significantly reduce human-factor failures.

3. CONCLUSION

Safety when working with ladders is achieved only when the loop of responsibility among three key factors is closed: **the manufacturer** (who maintains quality through annual factory audits), **the employer** (who ensures systematic inspections), and **the worker** (who adheres to the three-point contact rule and performs visual checks).

Practical implications: Employers must transition from viewing ladder safety as a basic legal formality to incorporating it into active risk assessment models. Implementing standardized pre-use checklists and refusing to patch or weld damaged equipment are immediate, low-cost measures that save lives.

Limitations and future directions: This review is limited by the lack of a centralized, publicly available national database in the Republic of Croatia detailing specific accident mechanisms (e.g., distinguishing ladder falls from scaffolding falls in state records). Future research should focus on utilizing wearable motion sensors to analyze real-time ergonomic stress and balance degradation during prolonged ladder use, providing field data to optimize safe-use duration limits.

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Professional paper

CHALLENGES AND OPPORTUNITIES OF RISK ASSESSMENTS

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Abstract: *The goal of the paper is to present challenges of assessing risks in automotive and production company in Croatia – specifically a company that designs, develops and manufactures luxury hypercars, where there is a mixture of well-known jobs, as well as processes not many health and safety experts in Croatia have had experience with.*

The paper will present appropriateness of current risk assessment prescribed method (factors keeping the Risk assessment static rather than dynamic document), following regulations (over-regulated administration or lack of regulation considering new technologies), best practice from foreign companies and how it can be implemented to make assessing risks more agile and more recognized by workers and responsible persons. Outcome of proposed framework is an example of partial risk analysis for testing vehicle in driving by a test driver, where hazards and possible outcomes are shown in a way not abstract to the user or any other person; a way that can have an impact on perception and understanding importance of proper risk identification and following prescribed measures.

Although the presented paper is mostly personal opinion and experience-based point of view of an automotive industry health and safety specialist, it can serve as an idea of a direction where health and safety system could improve to keep up with foreign good practices and contributing to raising safety awareness in Croatian research, development and production companies.

Keywords: *risk assessment, health and safety, challenge, regulation, opportunity, worker, responsible person*

1. INTRODUCTION

How sure are we that Risk assessment is done properly? We often find many companies and health and safety specialists creating Risk assessment just to be compliant with the law, but those thinking of is the Risk assessment user friendly and will it benefit the workers are in minority.

Article 18. of Croatian Health and safety Act allows employers to have Risk assessment in written or electronic form [1]. But how much do we use the electronic version in practice and how is it implemented?

It is commonly accepted in Croatia (based on documentation the Inspectors ask when conducting inspection) that Risk assessment is a single document containing all prescribed information. Method of analysing risks is prescribed via matrix, which does not prevent you from additionally using another method. But in practice, using other methods is probably reserved for research work rather than everyday use by health and safety professionals. Even the online tool is only to be used for certain jobs if the Ministry of Labor approved it on their web pages [2]. If Risk assessment is not a single document containing all the information, how will it be subject of discussion at health and safety committee? And if the health and safety committee must "accept" the Risk assessment, how can it be expected to have a fully valid one, accepted by the company, and for it to always be compliant with current state if health and safety committee must meet only once every 6 months? In short, we cannot.

Fast growing, research and development-oriented company such as luxury hypercar development and production company (not excluding any other industry) would benefit from being able to freely draft Risk assessments in a way most suitable for its inner processes. It should be up to everyone in health and safety system to keep up and continuously improve recognition of appropriateness of provided documentation, regardless of type of form the Risk assessment is presented in. At very least, health and safety system should not limit framework of its own development at the very basics of its existence – assessing risks.

2. DAILY CHALLENGES AND OPPORTUNITIES OF RISK ASSESSMENT IN HYPECAR PRODUCTION INDUSTRY IN CROATIA

Although the Risk assessment allows some freedom in creating the document, since it is not strictly prescribed in its visual form there are limits to what can be done.

Risk assessment analysis form within my company of employment consists of:

- Job description (real process, not HR description)
- List of job titles that are designated to do the process
- Is the process determined to be a job with special working conditions, and if yes, by which regulation/points of regulation
- Does the job require working on a computer for more than half of workday
- Number of workers doing or planned to do the process (male, female, minors, persons with disability)
- Expert educations and trainings required for the process
- Vulnerable groups of workers; determining if they are allowed to work the process or not (minors, pregnant women, women who have recently given birth, workers having professional disease, and workers who are determined to have lowered residual working capability or are at direct risk of having decreased working capability) – and for prevention, which of them could be allowed only with approval from occupational medicine specialist

- Working hours and shifts
- Places of work and work areas
- Personal protective equipment to be used while doing the process
- Work equipment and means of work used
- Distribution of hazardous chemicals used by categories
- Use of diisocyanatos
- Need for calculating exposure to statodynamic exertions in accordance with Rulebook on protection of workers who are exposed to statodynamic, psychophysiological and other exertions at work (OG 147/21)
- Analysis of risks by applying risk matrix and required points of check compliant to Rulebook on creating risk assessment with general rules, actions, measures, and activities to reduce the risk.

All other mandatory content is also part of Risk assessment document, but the lists of chemicals, work equipment, appointed first aid providers, evacuation leaders, authorized officers and general data changes daily in fast growing companies that have research and development, new materials, as well as the "usual" parts of business as office work and production – which is the case in a luxury hypercar development and production company. Although in general this kind of analysis gives health and safety specialists and the employer legal coverage in case something happens, and a solid base of data/requirements to be followed up for every-day work, it does not mean that everyone included in the system understands the real importance of Risk assessments, how to read them, and how they help safety and health of employees. You assess the current state. You give information if something is low, medium, or high risk. But how did we get there? What was the starting state? What would happen if we did not implement any of the measures?

While exchanging experiences with people from different and foreign (non-EU) industries (health and safety professionals in automotive industry and foreign shipyards), I developed opinion that Risk assessments as prescribed in our regulations are over-regulated (detailed way of must-do's) and under-regulated (not aligned with other regulations, outdated) at the same time. They give you freedom to use another method, but not without the prescribed one first. You must name the recognized method and how you got everything, instead of focusing on possible outcomes to bring everything closer and more understanding to the workers who do the jobs we analyse. And doing both methods (prescribed one, and setting new framework and conducting a second one) for analysis of the same process is time spent, not time invested in the eyes of most employers. Laws and rulebooks of such a broad area as health and safety should give you just a framework of what should be done, not a step-by-step guide or limitations. If we would use more complex matrix, e.g. 5 x 5, no matrix at all, or if it is left to the experts to use what they see fit for the industry they are in, we would see growth of personal accountability and ideas for improvement - just like with any management standard you implement. The auditors cannot decide how something should look, but you must be able to prove you are compliant and have it under control.

If Risk assessment is of real use only to health and safety specialists in charge of analysing risks, we cannot expect for safety culture in Croatia to change. And lack of knowledge and understanding or recognizing the risks by health and safety specialists is not a reason to give them (us) done solutions and prescribed forms. If we focus on the critical thinking and the outcome, level of risk before any measures, and level of risk with measures implemented, Risk assessments would have greater impact at workers' understanding of health and safety and how it benefits them. Employers

as well as authorized officers would have better overview of potential outcomes they personally are responsible for. Although there is an obligation for workers and representatives of the employer to be included in the Risk assessment, this part is not defined in a way that would ensure improvement of risk assessments, true awareness of risks, and determining responsibilities of implemented in case of major incidents. Yes, the authorized officer is responsible. But what about process engineer that created that process?

When you give freedom to company on how health and safety is to be organized within the company and set a strong framework with noticeable consequences, you are building more than legal compliance – you are building a true system with improvements, not just a law compliant document. Process risk analysis would be much more up to date if you can easily change value in a form, daily, based on how the process in fast-pacing development company changes, without needing to update unrelated information. It should not be dependent only on health and safety specialist (while respecting inclusion of workers in making of Risk assessment). Person responsible for the process should also be listed as signee of the process analysis. That way, you ensure proper ownership and accountability. I, as a health and safety specialist, may never know what's it like to test-drive a hypercar in development, which systems can fail and cause me to run off the track, but experienced test driver surely can, and he can recognize process specific risks better than anyone in the company. He would be the first responsible to notify if something changed and risk needed to be re-analysed. If the state would recognize that Risk assessment can be multiple electronic, live documents that are not depended on each other but are very much interconnected, risk assessment would be more agile, and you would be able to assess immediate risk at current time and adjust the risk analysis and measure even by a minute. That would give true meaning to "live" Risk assessment document.

It does not matter if a process is done by 2 or 10 persons, as long as all the conditions and requirements of area are met. In large companies' number of workers fluctuates on a daily base. Names of workers designated to provide first aid, evacuation leaders, as well as list of authorized officers changes frequently. Wouldn't it be easier that workers always have live, digital access to that information in multiple nicely arranged documents, rather than "confirmed" one as part of Risk assessment discussion on health and safety committee once every 6 months?

For this short paper we will not go into the deep dive of challenge named categorization of chemicals by the directive and categorization of chemicals within current Risk assessment forms. They are not that easily relatable, and for company that uses hundreds of chemicals it could be easily analysed completely wrong if you do not have responsible and diligent Person responsible for chemicals. Having this part properly analysed is a huge impact on workers long-term health, and not many companies in Croatia give enough attention to details of it. The need of expert education and medical examinations for special working conditions may not be changed for a long time (especially with regulation from 1984. not updated to catch up with new technologies and findings), but weather or microclimate conditions in which the worker can do the process, or specific brand of a chemical can change by the hour.

You would still need to have all the trainings, but maybe the focus can be moved to a path where health and safety specialist can only train worker for general and practical health and safety information (as obligations and responsibilities, location of first aid kits, assembly points, organize fire prevention trainings, show evacuation routes, daily checks of workplace and machines, reporting injuries, near misses and accidents procedure, usage of personal protective equipment, where to find all instructions and Risk assessments - in which we can train the workers); and leave the official "process training confirmation" to persons who are expert in the process. If every worker signed

every set of work instruction and process risk analysis, and every small change in information he received by his authorized officer, it would be so much easier to determine where the mistake or missing out happened if unwanted events come our way.

3. PROPOSED FRAMEWORK POSSIBILITY AND OUTCOME

Expected concern would be; if it is not prescribed like it is now, how would you prove you do it regularly and properly. With all the technology today, it is quite easy to maintain digital database and archive with published/approved dates. If anything, ISZNR (informational system of occupational safety) is an existing tool both inspectors and health and safety specialists can use for the database of processes. Other information is anyway just something you take into consideration when analysing risks, and if considered does not affect the outcome, it is not of a huge importance.

Table 1, Table 2 and Table 3 show one of proposed possibilities of slightly delimited framework for assessing risks.

Table 1: Risk rating matrix [3]

Likelihood × Severity	1 Negligible	2 Minor	3 Moderate	4 Major	5 Catastrophic
5 Almost certain	5	10	15	20	25
4 Likely	4	8	12	16	20
3 Possible	3	6	9	12	15
2 Unlikely	2	4	6	8	10
1 Rare	1	2	3	4	5

Table 2: Risk band [3]

Risk band		Score	Required action
	Low	1 – 4	Risk acceptable. Maintain existing controls and monitor.
	Moderate	5 – 9	Tolerable. Reduce risk as far as is reasonably practicable; review controls periodically.
	High	10 – 15	Substantial. Additional controls required before work proceeds; assign an owner and timescale.
	Very high	16 – 25	Unacceptable. Stop or do not start. Take immediate action to reduce risk to at least moderate.

Table 3: Definitions of likelihood and severity [3]

Likelihood (how likely is it to happen?)		Severity (how bad would the harm be?)	
1	Rare — may occur only in exceptional circumstances.	1	Negligible — first aid only, no lost time.
2	Unlikely — could occur occasionally.	2	Minor — minor injury, short absence.
3	Possible — might occur at some point.	3	Moderate — injury needing medical treatment; RIDDOR over-7-day.
4	Likely — will probably occur in most circumstances.	4	Major — serious or specified injury, hospitalisation.
5	Almost certain — expected to occur in most circumstances.	5	Catastrophic — fatality or multiple serious injuries.

Below is an example of how a partial analysis of process Risk assessment for test driving of an electric hyper car could look like (Table 4 and Table 5).

Table 4: General Risk assessment internal form example

TESTING OF VEHICLE IN DRIVING – TEST DRIVER level A				
Special working conditions jobs based on Rulebook on special working conditions OG 5/84:	Yes	☒	No	☐
Article 19 – special regulation, Rulebook on health examinations of drivers and candidates for driver OG 51/24 (when renewing driving license), and additionally internally prescribed medical examinations and educations for test drivers				
Job description				
Vehicle testing on the proving ground and roads - performance testing, high speed limit management, Vehicle assessment, tire testing, high speed testing, heavy handling, shock absorber testing. Instructional work at other driver training sessions. Vehicle safety, compliance, and compliance assessment basics. Track driving, performance driving, heavy handling, road testing. Mule and Proto shakedown testing and safety assessment, vehicle safety checks, endurance testing, brake calibration, marketing events.				
Mandatory educations:				
Health and safety training, Fire extinguishing training, National Driver license B category, Internal test driver permit				
Vulnerable categories of workers allowed to do the job:				
Minors	Yes ☐	No ☒		
Pregnant women	Yes ☐	No ☒		
Women who have recently given birth	Yes ☒*	No ☐		
Women who are breastfeeding	Yes ☒	No ☐		
Workers who have professional disease	Yes ☐	No ☒		
Workers who are determined to have lowered residual working capability or are at direct risk of having decreased working capability	Yes ☐	No ☒		
*Note: only with approval from occupational medicine specialist				
Work schedule:	Single shift and field work, 08:00-16:00 h			
Work areas and places of work:	Proving ground/test tracks, public roads, client locations			
Mandatory Personal Protective equipment				
Based on conditions of testing/driving needs: Race suit FIA 8856-2018 Gloves FIA 8856-2018 Shoes FIA 8856-2018 Underwear FIA Standard 8856-2018 Protective helmets - FIA Standard 8859-2015 and Snell SA2020 HANS FIA 8858-2010				
Work equipment and means of work used:	Homologated and non-homologated vehicles, development vehicles			

Table 5: Outcome risk analysis form(partial) for TESTING OF VEHICLE IN DRIVING – TEST DRIVER level, inspired by foreign practices [3]

Hazard	Who could be harmed	How they could be harmed	Initial risk	Existing controls	Residual risk	Additional actions required	Person responsible for implementation of measures
Traffic accident or a car accident on public road	Driver, passenger, other participants in traffic, pedestrian, animals	Death, hospitalization, or medical treatment required, Impact by a car or a part of objects impacted by the car	20	–Approved car in a road-safe condition, Test specific risk assessment –Valid drivers' permit, Internal driving permit and authorization, Medical examinations for test drivers, Cognitive and physical preparation of test drivers, Health and safety training –Respecting traffic rules, Car equipped with first aid kit –Using protective devices (seatbelt, automatic systems for aiding the driver) and personal protective equipment –testing for presence of addictive substances	8	–Periodical checks of first aid and emergency kit content –Medical examinations after accident/incident or in case of suspecting state that could impact drivers' abilities –Ensuring enough rest of the driver, not operating if fatigue levels increased	Vehicle Development Engineer responsible for the vehicle, Chief Development Driver by xx.yy.zzzz.
Accident with a non-homologated car on a racetrack	Driver, passenger, proving ground staff	Death, hospitalization or medical treatment required, Impact to solid obstacles, running of the racetrack	25	–Approved car in a road safe condition for specified test, Roll Cage –High-performance experienced driver –Test specific risk assessment done –Identifying hazardous zones during the tests, setting protective barriers around the track to protect bystanders, checking functionality of safety and emergency systems in the car before test drive –Valid drivers' permit, Internal driving permit and authorization –Medical examinations for test drivers, Cognitive and physical preparations of test drivers, Health and safety training –Emergency team on standby on the racetrack –Using protective devices and personal protective equipment, prescribing allowed manoeuvres –Ensuring enough rest of the driver, not operating if fatigue levels increased	15	–Adaptation of test specific risk assessment based on weather and road conditions –Limiting speed of planned tests –Limiting number of people included in the test vehicle(with or without passenger) and nearby hazardous zones	Vehicle Development Engineer responsible for the vehicle, Chief Development Driver by xx.yy.zzzz.
Electrocution by a DC HV battery in development car or in a crash	Driver, passenger, other participants in traffic, fire department	Death, hospitalization or medical treatment in case of close contact with the damaged car or connections to HV battery	15	–Approved car in a road-safe condition –No visible damage to connections –Revalidating car by expert personnel with appropriate PPE in case of minor accidents –Removing all persons from contact and zone of possible contact with the battery or a car in case of a crash –Sharing battery hazards and to the fire department	5	–If applicable share new findings on battery safety with firefighting community –Reevaluate measures if new findings or new circumstances occur	Employer, Vehicle Development Engineer and persons responsible for fire safety and health and safety
Fire and explosion hazard	Driver, passenger, other participants in traffic, nearby standers, fire department	Death, hospitalization, medical treatment or minor injuries in case of a crash or thermal runaway of the battery	15	–Approved car in a road-safe condition –Experienced and medically fit driver –Checking functionality of safety and emergency systems in the car before test drive –Valid drivers' permit –Internal driving permit and authorization –No visible damage to battery or its connections –Removing all persons from hazardous area in case of a crash or thermal runaway –Fire extinguishing training –Fire extinguisher in the vehicle or nearby –Emergency services standby on the racetrack –Using prescribed personal protective equipment	8	–Reevaluate measures if new findings or new circumstances occur	Employer, Vehicle Development Engineer and persons responsible for fire safety and health and safety
Static and dynamic exertions	Driver, passenger	Minor consequence to locomotor system due to high G forces	10	–Car with proper/ergonomic seat and steering –Usage of proper protective devices (restraints) –Organizational measures, limiting time of exposure to exertions	6	–Reevaluate measures if new findings or new circumstances occur	Vehicle Development Engineer, Chief Development Driver

3. CONCLUSION

Drafting of Risk assessment document in most Croatian companies today is like marking a checkbox for a task. It is done, they have all the processes, legal form is met and workers have participated. In practice, not many besides the health and safety specialists understand what could happen if risks are not properly analysed, what are the rare, but worst possible outcomes, or how big of an impact implementing even simple measures could have. Having impact-based point of view Risk assessment could influence changing health and safety awareness of employees, safer approach to processes in general, and could also lead to employees standing up for safer workplaces. Small delimitation of risk analysis forms could, through the mentioned, contribute to health and safety not being seen an expense, but as an investment in a safe work environment by the employers. In practice and in a dynamic industry such as hypercar design, research, development and production, it will take time and lots of effort to be able to conduct a second method of Risk assessment analysis in addition to prescribed one. Small delimiting in regulating risk assessment methods would benefit health and safety specialists immediately, and consequently employees whose protection and safety is at most importance to everyone in the system.

The system would make even more sense if we would follow foreign examples of having mandatory insurance policies related to health and safety. Having mandatory medical examinations for all employees before start of work, and when leaving the company can also contribute greatly. If it is noticed workers leaving the company are not of same health as when they first started, it means company might have skipped to properly analyse and implement measures to reduce risks and hazards – and it is an area which can be improved. That could be the starting point where inspection

can give the company direction and advice, or where they can investigate when serious injuries or incidents occur. Employers would still be punished by insurance companies with increased prices of their premiums, which is not on any employers' wish list.

And if "live" and more agile Risk assessments were implemented, just think of how fulfilling would it be if every worker develops greater health and safety consciousness, recognizes possible major or catastrophic outcome and could instantly be aware how a small measure like proper training or waiting for the right time/conditions to do something could save his or his colleagues' life.

REFERENCES

[1] Croatian Health and Safety Act OG 71/14, 118/14, 94/18, 96/18

[2] Rulebook on creating a Risk assessment OG 112/14, 129/19

[3] Risk assessment template, *Available from* https://keyostas.co.uk/risk-assessment-template/ , *Accessed*: 2026-06-11

Professional paper

WORKS AND RESPONSIBILITIES ON THE CONSTRUCTION SITE WITH CODE-REQUIRED CONSTRUCTION SITE TESTING AND INSPECTION

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***Abstract**: On temporary construction sites, all participants face certain challenges, with contractors facing the greatest difficulties, as they are responsible for constructing, reconstructing, or adapting a building in accordance with the project documentation. In doing so, they must take into account all workers, work equipment and machinery, supervisory authorities, and the investor, while ensuring that all activities are carried out in compliance with applicable laws and regulations. (Occupational Health and Safety Act (NN 71/14, 118/14, 94/18, 96/18) [1], Labor act (NN 93/14, 127/17, 98/19, 151/22, 64/23) [2], the Construction Act (NN 155/25) [3], and the Criminal Code (NN 125/11, 144/12, 56/15, 61/15, 101/17, 118/18, 126/19, 84/21, 114/22, 114/23, 36/24, 136/25) [4].*

Keywords: construction site, the contractor, construction site participants, the investor, Workers, supervisory bodies/inspectorate, prescribed testing, laws

1. INTRODUCTION

This expert overview presents the fundamental issues present on every construction site, regardless of its size, in accordance with the Occupational Health and Safety Act (NN 71/14, 118/14, 94/18, 96/18), the Construction Act (NN 155/25), and the Criminal Code (NN 125/11, 144/12, 56/15, 61/15, 101/17, 118/18, 126/19, 84/21, 114/22, 114/23, 36/24, and 136/25).

A construction site begins with the investor introducing the contractor to the job through the Record of Handover and Site Takeover. At that moment, the contractor's responsibility begins.

Participants on the construction site are:

- the investor, owner of the building, concessionaire, or another person for whom the main design is prepared
- the contractor (main contractor, subcontractor, cocontractor, and any contractor engaged directly by the investor outside the main contractor)
- supervision (supervising engineers, OHS coordinators, inspection authorities)

All of them must comply with the laws.

This overview highlights existing reallife problems faced by all participants, with emphasis on the contractor and all their obligations, including all construction site testing and inspection on construction sites.

2. INVESTOR OBLIGATIONS UNDER THE OCCUPATIONAL HEALTH AND SAFETY ACT (ARTICLE 73)

The investor is required to:

- apply general principles of prevention and occupational safety rules in all phases of design and project preparation (paragraph 1)
- ensure that an occupational safety study is prepared during the design of buildings intended for work, in accordance with special regulations (paragraph 3)
- appoint one or more OHS coordinators during project design and construction when two or more contractors perform or are expected to perform the work (paragraph 4)
- ensure preparation of the Work Execution Plan before establishing the construction site (paragraph 5)

Under Article 75 of the Occupational Safety Act, the investor must:

- no later than one day before the start of work on a temporary site where work will last more than five days and involve two or more contractors, submit a notice of commencement of works to the Labour Inspection Authority (paragraph 1)
- list the contractors who will perform work on the site (paragraph 2)
- no later than one day before the start of work, submit a construction site notification to the Labour Inspection Authority for sites involving two or more contractors (paragraph 3)
- ensure that the Work Execution Plan is present on the site (paragraph 5)
- update the notification in case of changes affecting the completion deadline, introduction of a new contractor, or temporary suspension of work (paragraph 6)
- **cannot transfer these obligations to the contractor (paragraph 8)**

And how does this usually look on our construction sites?

Investors—in this case legal entities—often do not prepare the occupational safety study for commercial buildings and do not appoint an OHS coordinator during the design phase, claiming they “didn’t know.” If the study is prepared, it often contains copypasted project sections. **The study should contain and describe how safety rules will be applied during the use of the building meant for work.** For example, for a carpentry workshop, it should describe safe delivery and internal transport of materials, technological processes, storage, worker facilities, and maintenance procedures.

State inspectors review these studies with the project documentation and often refuse to approve building permits due to poor OHS studies.

Investors frequently fail to notify the State Inspectorate about the start of works, believing it is expensive or timeconsuming. In reality, it costs nothing and requires only one form sent by email.

A major issue is that investors do not prepare the Work Execution Plan during the design phase. During construction, they often shift this obligation to the main contractor through the contract. If the contractor refuses, they do not get the job. This is common with large investors. They often claim the plan is unnecessary for buildings under 400 m².

3. CONTRACTOR

3.1. Legal obligations

Article 22 of the Construction Act requires the contractor to perform work in accordance with the building permit, the law, technical regulations, special regulations, and professional standards. Article 23 paragraph 6 requires the chief site engineer and/or site manager to ensure the completeness and coordination of the works.This also carries criminal liability under Articles 215–222 of the Criminal Code.

How to protect the chief engineer/site manager?

The Chief Engineer/Site manager should ensure completeness and coordination of works through a formal legal act—such as a decision or directive—defining site organization.

3.2. Types of contractors

Main contractor — signs the contract with the investor

Subcontractor — contracts work with another subcontractor or a nominated subcontractor; the main contractor is often unaware of the last subcontractor in the chain

Cocontractor — also signs agreement with contractor, but a different type of agreement than a subcontractor

Contractor hired directly by the investor, unknown to the main contractor

This creates chaos on the construction site.

3.3. What must the main contractor ensure?

Under the Occupational Health and Safety Act:

- application of basic OHS rules (with special attention on mechanical hazards, electrical hazards, ie. work in relation to construction site testing and inspection)
- application of special OHS rules
- preparation of an OHS risk assessment
- organization and implementation of OHS in all work processes and all parts of work organization; so the **OHS specialist must be present at construction site and must work according to the law**

- assure training of workers for safe work
- provide instructions for a safework environment
- provide medical examinations for workers performing jobs with special conditions
- prohibition of assigning specialized tasks to unqualified workers and to the ones without any proof (**a major issue with foreign workers**)
- providing collective and personal protective equipment (PPE)
- **testing work equipment, tools, and the work environment**
- control of chemical use
- control of biological hazards
- fire protection, evacuation, and rescue measures
- ensure first aid
- protection of nonsmokers
- prohibition of alcohol, drugs, and intoxicants

In reality there are a lot of issues surrounding these:

In order for an employer to ensure the application of basic and specific occupational health and safety rules, they must prepare the fundamental OHS document, which is the risk assessment. Very often, risk assessments are prepared using templates, and in doing so the specific characteristics of the employer are neglected from the outset. The risk assessment must clearly state what tasks the worker performs, under what conditions, and with what equipment. If this is properly described, then the risks to which the worker is exposed can be accurately assessed. It should be emphasized that risk assessments are often simply copied from others. It must also be pointed out that in reality it is not possible to identify and predict all risks to which a worker is exposed, which creates a major problem for the employer in the event of an incident, particularly a workplace injury.

A major issue is the way occupational health and safety tasks are carried out. Smaller employers, with up to 49 employees, enter into contracts with authorized OHS companies, which then assign one of their OHS specialists to that employer. Often, a specific number of working hours is defined for that specialist. In practice, this specialist works full-time at their own company and **visits the construction site perhaps once every two weeks to check working conditions. Such visits usually last no more than half an hour, as the specialist must quickly return to other duties.**

Employers with more than 50 employees must hire an OHS specialist under an employment contract and register them with the pension insurance system. However, the law does not define how many working hours this specialist must be employed for, so employers often contract them for only one or two hours per week. This is cheaper and formally satisfies legal requirements, while the actual situation remains essentially the same as in the previous case. Some employers do hire full-time OHS specialists who perform their duties properly, but others employ engineers full-time who then simultaneously handle OHS, fire protection, environmental protection, and various administrative tasks—making OHS a secondary concern.

How to properly train workers to work safely in all tasks they perform? With some difficulty. Should it be done through authorized organizations or internally by each employer with their own engineers? The best approach is to do it internally, as the employer knows best the conditions and tools their workers use.

Jobs with special working conditions require mandatory medical examinations. Due to a shortage of occupational medicine doctors, these are often conducted superficially—for example, a worker may simply state that they are allergic to dust or chemicals, and the doctor records this without conducting proper testing.

A significant problem is foreign “expert” workers. Work permits are often issued based on the worker’s own statement of their profession. As a result, we encounter masons, steel fixers, and carpenters who lack even basic skills, yet their work permit states they are qualified. Employers face serious difficulties: in employment contracts they must state that the worker performs the role listed in the permit, while in the risk assessment they must describe the actual job and risks, and in official forms they must describe the real tasks performed—which are often those of a general construction laborer. This creates major issues during inspections or in the event of a workplace accident.

Another major issue is Instructions for safe work. How can they be written in a way that workers—such as those from Nepal, the Philippines, or India—can understand? Perhaps the situation will improve if language requirements are introduced. The same problem applies to working with chemicals and biological hazards.

Protective equipment presents another major challenge. Collective protective measures are preferred, but construction conditions often make them impractical (e.g., safety nets). For hazardous gases, sensitive detection devices should be used. This leaves personal protective equipment (PPE). Employers must provide appropriate PPE, and workers must use, maintain, and clean it. This includes everything from helmets and safety shoes to harnesses for fall protection. However, even when equipment is provided, workers often refuse to use it because it “gets in the way” or slows them down. This raises the question: how should such behavior be sanctioned?

3.4. Prescribed Testing

Employers must regularly conduct testing of:

- Electrical installations
- Work equipment
- Tools

Testing intervals are regulated both in Croatia and in the EU. In Croatia work equipment must be tested every 3 years and electrical installations every 4 years according to rule book. In the EU, work equipment is typically tested every 6 months.

Employers in Croatia are trying to do so every 3 years. In practice, especially in construction companies, the situation is different. Machinery is frequently moved between sites, breaks down, and undergoes repairs. After major repairs, obligatory re-testing is often neglected. Sometimes safety devices (e.g., emergency stop buttons) are faulty, but mechanics may dismiss their importance. This disrupts the testing cycle.

Another issue is that inspectors may not be available when testing deadlines expire. Employers often rely on documentation rather than actual safety. In some cases, documentation is issued without real inspections. Ironically, companies that perform thorough checks may make minor documentation errors and face consequences, while others produce flawless paperwork without proper inspections.

There are also cases where employers request testing of tools like chainsaws or grinders—although not legally required—creating complications for testing authorities.

Although employers generally follow prescribed intervals, the question remains whether this is sufficient, and why the EU insists on shorter intervals for tests.

Construction equipment is exposed to harsh conditions and materials such as concrete, metal, and stone, and is frequently repaired. A three-year interval is too long—some equipment becomes unusable within that period.

Recommendation:

- Daily checks before and after use
- Testing at least every 6 months
- Internal inspections by company engineers, then using color-coding systems (e.g., yellow for first half of the year, blue for second)
- Electrical testing includes:
- Scaffolding grounding
- Temporary distribution boards
- Container grounding
- These checks are often overlooked, although they can be life-saving.

3.5. Workers

There is **no formal system for punishing workers under OHS law**—only the obligation to work with due care.

However, under OHS laq employers must remove workers who:

- Do not use PPE
- Work with work clothes where safety devices have been removed
- Bring or use alcohol or drugs or other opiates

4. OCCUPATIONAL SAFETY COORDINATOR DURING THE CONSTRUCTION PHASE

Tasks are defined by Article 77 of the Occupational Health and Safety Act; however, it is essential to determine the coordinator's presence on the construction site. The Act and the relevant bylaw do not prescribe the extent of presence required for the occupational safety coordinator during the execution phase. An "appropriate number of hours" is referenced. Does this imply 1 hour per day, full-time presence every day, or once per week? Within the EU, it is generally understood that this role is almost always performed on a full-time basis on larger construction sites or when hazardous works are being carried out. The coordinator's duties are defined by statutory provisions. Records are also maintained, which can be found online. These typically consist of tabular forms in which neither the machinery nor equipment used on the construction site are specified, nor is there

documentation on how the operational integrity or compliance of such equipment has been verified. Instead, only tables with entries in the form of "+" or "–" signs are provided.

However, coordinators often express dissatisfaction with one another regarding the pricing of their services; thus, it is commonly highlighted that for a particular construction site one offer amounted to EUR 300 for one month of work, while another offer amounted to EUR 1,600 for the same site. Naturally, the investor selects the EUR 300 offer. In practice, however, it makes little difference which coordinator is selected, as both typically attend the construction site once per week, given that they are otherwise employed full-time by another company and therefore cannot be continuously present on site. Very frequently, occupational safety coordinators simultaneously act as supervising engineers on the same construction site. Consequently, a situation may arise where a record entered in the coordinator's log indicates that the concrete is of inadequate quality. Alternatively, in the capacity of supervising engineer, the same individual may approve the use of scaffolding that has not been properly constructed and lacks a design, resulting in a structural failure and a worker falling. In such a case, how can the individual, acting as a coordinator, issue an order to himself in his role as supervising engineer to prohibit the use of such scaffolding?

Nevertheless, even if the coordinator performs their duties diligently and identifies a non-compliance, what actions are they required to take? Does the contractor comply with their instructions? Or the investor? What enforcement mechanisms does the coordinator have to ensure that both the contractor and the investor act in accordance with their directives? The investor may assert that they are financing the coordinator and therefore expect compliance with their own expectations—but what about the contractor?

5. WHO IS LIABLE UNDER THE CRIMINAL CODE FOR OMISSIONS ON A CONSTRUCTION SITE IN THE EVENT OF A WORKPLACE INJURY?

The procedure is as follows:

The employer is obligated to notify the occupational safety inspector immediately upon occurrence of the incident and after first aid has been provided to the injured person. The inspector attends the construction site, establishes the facts, collects statements, and ultimately prepares an official report. Based on the findings, the inspector determines and identifies those responsible for the omissions. In most cases, this includes construction site engineers, persons authorized by the employer to implement occupational safety measures, site managers (foremen), and may also include individual workers, such as a forklift operator. Additionally, liability may extend to the occupational safety professional, the occupational safety coordinator, and the supervising engineer. The inspector then submits a proposal to initiate criminal proceedings to the State Attorney's Office. The prosecution examines witnesses and any other relevant individuals it deems necessary; it may dismiss certain suspects or include additional ones, and ultimately files a criminal indictment before the competent criminal court.

LITERATURA:

[1] Zakon o zaštiti na radu (NN 71/14, 118/14, 94/18, 96/18),

[2] Zakon o radu (NN 93/14, 127/17, 98/19, 151/22, 64/23)

[3] Zakon o gradnji (NN 155/25),

[4] Kazneni zakonom (NN 125/11, 144/12, 56/15, 61/15, 101/17, 118/18, 126/19, 84/21, 114/22, 114/23, 36/24 i 136/25).

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APPLICATION OF THE HEART TECHNIQUE FOR HUMAN ERROR ASSESSMENT IN HIGH-RISK WORK ACTIVITIES

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Abstract: *The causes of failures in highly reliable technical systems, excluding the influence of external environmental factors, are predominantly associated with the human factor. The most common sources of system unreliability are operator errors, including tasks performed incorrectly, performed late, or neglected. Due to frequent errors made by operators during the issuance of work permits and the implementation of control procedures, the need to apply methods for quantifying human errors within the management system for high-risk work activities has been recognized. The aim of this paper is to present the practical application of the Human Error Assessment and Reduction Technique (HEART) in the execution of high-risk activities in the company Power plants of North Macedonia (AD ESM). The application of this method enabled the quantification of the probability of identified errors, as well as the definition of measures for their mitigation.*

Keywords: *human error, high-risk work activities, HEART, human error mitigation.*

1. INTRODUCTION

The nature and frequency of accidents in occupational and living environments have important implications for safety, productivity, and the efficiency of human activities, as well as for the functioning of technological systems as a whole. The five key components of a successful business—human resources, machines, materials, procedures, and the work environment—individually or collectively generate factors that contribute to system risk [1].

Human error represents one of the significant factors affecting system reliability and safety, particularly in high-risk work activities where even the smallest oversight can lead to serious consequences. High-risk work activities refer to tasks associated with an increased probability of accidents, injuries, material damage, or threats to human health and the environment. These

activities are typically performed under complex and hazardous working conditions and are present across various sectors, including energy, construction, mining, healthcare systems, and emergency response operations [2]. A permit-to-work system serves as a management tool for controlling high-risk work activities and aims to ensure the implementation of an appropriate control system for identified risks associated with such activities. Due to the frequent occurrence of operator errors during the issuance of work permits and the application of control systems, the need for methods to quantify human errors within high-risk work activity management systems has been recognized.

Human errors are undesirable actions or activities that result in deviations from expected standards or norms, thereby placing people, equipment, and systems at risk [3]. James Reason defines human error as the failure of planned actions to achieve intended objectives, occurring without the influence of external or unpredictable events [4].

Human error may be triggered by various factors, such as insufficient operator qualifications, lack of precision, cognitive failures, reduced concentration, or an inability to understand and follow procedures. Therefore, human errors are considered a consequence of human performance. Human performance depends on numerous factors referred to as Performance Shaping Factors (PSFs). These factors can either increase or decrease the Human Error Probability (HEP), depending on individual characteristics, environmental conditions, work organization, task complexity, and similar aspects [5, 6].

For the purpose of effectively reducing human errors, Human Reliability Assessment (HRA) plays a key role. Most existing human reliability assessment methods are quantitative approaches (e.g., Human Error Assessment and Reduction Technique (HEART), Technique for Human Error Rate Prediction (THERP), Success Likelihood Index Method (SLIM), etc.), which are based on Probabilistic Risk Assessment (PRA) [7].

This paper presents the practical application of the HEART method for assessing human error during the execution of high-risk activities in the company Power plants of North Macedonia (AD ESM).

2. METHODOLOGY

The HEART method is a quantitative approach for human reliability assessment developed by Williams in 1986 [8]. The method is applicable across various situations and industries, including the chemical, aviation, oil, medical field and so. It is based on the assumption that every operator task execution carries a possibility of failure, with the HEP being influenced by various Error Producing Conditions (EPCs). By analyzing EPCs and evaluating working conditions, it is possible to calculate the probability of human error occurrence and, consequently, assess the reliability level of task performance [9]. The HEART procedure consists of six steps [7, 10].

Identification of Human Error represents the process of applying various guidelines and procedures to determine the possible causes of human error occurrence within a specific scenario. This approach enables a qualitative analysis of different types of errors and contributes to a better understanding of potential system failures, thereby facilitating further assessment and quantification of errors by experts.

Task Quantification has a significant impact on HEP estimation, since the conditions contributing to errors essentially increase the nominal HEP value. Nominal Human Unreliability (NHU) is determined by classifying task types, such as complex, routine, or other categories of activities [see more 7].

Identification of EPCs represents an important step in determining HEP, as these factors negatively affect human performance and increase the probability of error occurrence. To obtain more realistic and accurate results, the use of a limited number of relevant EPCs is recommended. Including a large number of EPCs may lead to a substantial increase in the nominal HEP value, even when less complex tasks are being analyzed. Therefore, only those EPCs that are clearly present within the observed scenario should be selected in order to maintain the objectivity of the assessment.

Expert Impact Assessment represents one of the most demanding steps in the application of the HEART method, as the degree of influence of each EPC factor is determined using the Proportion of Affect (POA) value within a range from 0 to 1. This assessment indicates the extent to which a specific factor contributes to an increase in the probability of human error. Low POA values (less than 0.1) indicate a negligible impact on the overall probability of error, whereas values greater than 0.9 indicate significant deficiencies within the system or the task itself. After the expert assessment (EA) is performed on a scale from 0 to 1, the total HEART effect (E) is determined according to equation (1) [7]:

$$E = ((ME \square 1) \times EA) + 1 \tag{1}$$

Where: ME – maximum HEART effect, EA – expert assessment of EPCs on analyzed system (assessed POA), E – assessed overall HEART effect.

Based on the classification of tasks and the assessed effect of each EPC, the total probability of human error is determined, as shown in equation 2 [7]:

$$HEP = NHU \times E_1 \times E_2 \times .. \tag{2}$$

Where: NHU – Nominal Human Unreliability for generic task; E1, E2... – Assessed overall HEART effect for EPCs.

Error Reduction is performed based on the assessment, nominal probabilities, and the ranking process. Error Reduction Mechanisms (ERMs) are not necessary if operator reliability is considered adequate. On the other hand, if error reduction is required, the impact and frequency of the corresponding human error identified through the analysis can be reduced by developing Error Reduction Strategies (ERSs).

Documentation is of great importance in human error assessment due to the need to ensure the validity of research results. Documentation should include an adequate database that provides a clear, verifiable, and applicable basis for human error assessment.

3. RESULTS AND DISCUSSION

The HEART was applied to quantify human errors identified through the analysis of 10 major HSE incidents in the field of industrial safety within the company AD ESM. The following characteristic human errors were identified:

1. Improper and imprecise issuance of work orders;

2. Error due to failure to issue a work permit;

3. Failure to implement the basic principles of work organization;

4. Inadequate cooperation between operators;

5. Incomplete implementation of workplace safety measures;

6. Omission of procedural steps during field operations;

7. Errors in routine operations requiring attention;

8. Communication errors;

9. Failure to use prescribed protective devices and safety equipment, and

10. Failure to use the required personal protective equipment (PPE).

The assessment of the identified errors was considered as an independent problem rather than as an integral part of the overall system risk assessment. For the investigated case, the following task categories were quantified:

E – a familiar, well-designed routine task performed by highly motivated, well-trained, and experienced operators who are aware of the possible implications of failures and have sufficient time to correct potential errors, with a proposed nominal human unreliability (5–95%) of **0.0004**.

G – a relatively simple task performed rapidly or with limited attention, with a proposed nominal human unreliability range (5–95%) of **0.09**.

D – a general, routine, highly practiced task requiring a relatively low level of skill, with a proposed nominal human unreliability range (5–95%) of **0.02**.

For the investigated case, the EPCs presented in Table 1 were adopted.

Table 1: EPCs for the case study

Nm	EPCs	Maximum HEART Effect (ME)
1.	Ignoring easily accessible information.	X 9
2.	Unclear allocation of functions and responsibilities.	X 1.6
3.	Incentives for using alternative procedures.	X 2
4.	Low workforce morale.	X 1.2
5.	Inadequate actions following performed control measures.	X 4

Nm	EPCs	Maximum HEART Effect (ME)
6.	Poor quality of information conveyed through procedures and person-to-person interactions.	X 3
7.	Insufficient checking or testing of output information.	X 3
8.	Inadequate training.	X 3
9.	Discrepancy between perceived and actual danger.	X 4
10.	Inadequate education of operators regarding assigned tasks.	X 2
11.	Inadequate transfer of spatial and functional information to operators.	X 8
12.	Lack of experience.	X 3

The overall HEP and the contribution made to unreliability modification for each task are presented in the following tables (Tables 2,3,4).

Table 2: Quantification of HEP for task E

NHU for generic task E (5-95%) 0.0004				
EPCs	**ME**	**EA**	**E**	**Contribution made to unreliability modification [%]**
Ignoring easily accessible information.	X 9	0.8	7.4	65.84
Unclear allocation of functions and responsibilities.	X 1.6	0.5	1.3	11.56
Incentives for using alternative procedures.	X 2	0.5	1.5	13.35
Low workforce morale.	X 1.2	0.2	1.04	9.25
HEP	0.006			

The HEP value of 0.006 represents the probability of the following human errors: Improper and imprecise issuance of work orders and Error due to failure to issue a work permit. Ignoring easily accessible information (65.84%) was identified as the primary factor contributing to the improper execution of activities in the analyzed case, followed by Incentives for using alternative procedures (13.35%), Unclear allocation of functions and responsibilities (11.56%), and Low workforce morale (9.25%).

Table 3: Quantification of HEP for task G

NHU for generic task G (5-95%) 0.09				
EPCs	**ME**	**EA**	**E**	**Contribution made to unreliability modification [%]**
Inadequate actions following performed control measures.	X 4	0.7	3.1	40.26
Poor quality of information conveyed through procedures and person-to-person interactions.	X 3	0.4	1.8	23.38
Insufficient checking or testing of output information.	X 3	0.1	1.2	15.58
Inadequate training.	X 3	0.3	1.6	20.78
HEP	0.96			

The HEP value of 0.96 represents the probability of the following human errors: Failure to implement the basic principles of work organization, Inadequate cooperation between operators, Incomplete implementation of workplace safety measures, and Omission of procedural steps during field operations. In this case, Inadequate actions following performed control measures (40.26%) was identified as the main factor contributing to the increase in the probability of human error. Particular attention should also be given to other contributing factors, including Poor quality of information conveyed through procedures and person-to-person interactions (23.38%), Inadequate training (20.78%), and Insufficient checking or testing of output information (15.58%), in order to reduce the occurrence of errors.

Table 4: Quantification of HEP for task D

NHU for generic task D (5-95%) 0.02				
EPCs	**ME**	**EA**	**E**	**Contribution made to unreliability modification [%]**
Discrepancy between perceived and actual danger.	X 4	0.7	3.1	32.29
Inadequate education of operators regarding assigned tasks.	X 2	0.2	1.2	12.5
Inadequate transfer of spatial and functional information to operators.	X 8	0.3	3.1	32.29
Lack of experience.	X 3	0.6	2.2	22.92
HEP	0.51			

The HEP value of 0.51 represents the probability of the following human errors: Errors in routine operations requiring attention, Communication errors, Failure to use prescribed protective devices and safety equipment, and Failure to use the required personal protective equipment (PPE). In this case, Inadequate transfer of spatial and functional information to operators and Discrepancy between perceived and actual danger (32.29%) were identified as the main factors contributing to the increase in the probability of human errors, followed by Lack of experience (22.92%) and Inadequate education of operators regarding assigned tasks (12.5%). Therefore, it is important to initiate the development of strategies for the assessment, prediction, and reduction of human errors in a timely manner.

4. CONCLUSION

Human Reliability Assessment is an important step in managing human errors and reducing system risk to an acceptable level. In this study, the Human Error Assessment and Reduction Technique was applied to quantify human errors during the execution of high-risk activities in the company AD ESM.

Based on the conducted research within AD ESM, it can be concluded that the application of the HEART enables the identification of potential human errors, the assessment of their probability of occurrence, and the determination of factors that have the greatest influence on human performance. Furthermore, the quantification of human errors and identification of EPCs indicate the necessity of reducing both the number and severity of errors, as well as emphasizing the importance of preventing their recurrence. Continuous improvement and updating of procedures, regulatory documents, and training programs will undoubtedly contribute to reducing the probability of errors.

It should also be emphasized that, in addition to technical and organizational measures, cognitive strategies play a significant role in the reduction of human errors, as they are aimed at improving thinking processes, decision-making, and information processing. These strategies may include the development of situational awareness, the use of checklists, enhancement of attention and concentration, implementation of standardized procedures, as well as training programs for stress and workload management. The application of these strategies can reduce the impact of the human factor, improve task execution reliability, and enhance overall system safety.

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Professional paper

INTEGRATION OF CONTRACTOR MANAGEMENT AND MAINTENANCE MANAGEMENT: A SYSTEMATIC HSE APPROACH IN THE INA GROUP

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Abstract: *This paper analyses the integration of Contractor Management (CM) and Health, Safety and Environmental (HSE) requirements with maintenance management systems implemented through SAP Plant Maintenance (SAP PM), SAP Service Management (SAP SM), and the Single Service Company (SSC) model within the INA Group. The aim of the study is to evaluate how the systematic integration of HSE requirements throughout the contractor management process contributes to improved safety performance, enhanced risk control, and more efficient maintenance execution. A process-based case study approach was applied, covering the tendering, contracting, execution, and HSE post-evaluation phases of maintenance activities. The analysis focused on the implementation of key HSE controls, including risk assessment, Permit to Work (PTW), Job Safety Analysis (JSA), Last Minute Risk Assessment (LMRA), and Lock Out Tag Out (LOTO) procedures, integrated with SAP-supported maintenance planning and supervision. The findings indicate that the integration of Contractor Management, SAP PM/SM, and the SSC model strengthens risk management, improves contractor oversight, increases operational transparency, and supports continuous improvement through Key Performance Indicators (KPIs) monitoring and HSE post-evaluation processes. The paper contributes by presenting a practical framework for integrating contractor safety management and maintenance management systems in complex industrial environments, with potential applicability in other high-risk industries.*

Keywords: *maintenance management, contractor management, HSE, SAP PM, SSC model, occupational safety*

1. INTRODUCTION

Oil and gas operations are among the most complex industrial activities in terms of occupational safety and risk exposure. Effective risk management requires the integration of operational planning with HSE requirements. Within the INA Group, this integration is achieved through Contractor

Management (CM) processes and Maintenance Management systems implemented in SAP ERP, specifically SAP PM (Plant Maintenance) and SAP SM (Service Management), supported by the Single Service Company (SSC) model. The objective of this research is to systematically analyse the role and impact of defined minimum HSE requirements in the execution of particularly hazardous activities within oil and gas environments. The paper focuses on the integration of these requirements throughout all phases of the contractor management process, including tendering, contracting, execution of works and HSE post-evaluation. Furthermore, the research aims to evaluate how the alignment of HSE procedures with maintenance planning systems and contractor management frameworks contributes to improved safety performance, strengthened risk control mechanisms, and enhanced efficiency of maintenance execution.

To achieve this objective, the paper addresses the following research questions [1,3]:

- **RQ1 (hazard communication):** How can hazards be effectively communicated to contractors and subcontractors during the tendering phase through preliminary risk assessment procedures?
- **RQ2 (definition of HSE criteria):** How should HSE criteria and expectations be systematically defined in relation to identified hazards and the assessed level of risk?
- **RQ3 (certification requirements):** Which certifications are required depending on the assessed level of risk in maintenance activities?
- **RQ4 (sanctioning of contractors):** How are contractors sanctioned in cases of non-compliance with defined HSE requirements?
- **RQ5 (role of SSC model):** What is the role of the SSC model in ensuring the implementation and compliance with HSE requirements in complex contractor environments?
- **RQ6 (Key Performance Indicators (KPIs) and HSE post-evaluation):** How do KPIs monitoring and HSE post-evaluation processes contribute to continuous improvement in contractor safety performance? [11].

2. METHODOLOGY

A process-based approach is applied to identify integration points between safety management and maintenance execution, focusing on how risk management tools are embedded in workflows and ensured through supervisory mechanisms. The paper focuses on analysing the implementation of defined minimum HSE requirements in the execution of particularly hazardous maintenance activities and their integration across all phases of the contractor management process. The research adopts a practical and applied perspective, with the aim of evaluating how structured HSE requirements contribute to improved safety performance, enhanced risk control, and efficient maintenance execution. The analysis covers key contractor management phases:

- Tendering phase – including preliminary risk assessment and communication of hazards to contractors and subcontractors,
- Contracting phase – definition of HSE criteria, expectations, and mandatory certification requirements based on assessed risk levels,

- Execution phase – application of operational HSE controls such as Permit to Work (PTW), Job Safety Analysis (JSA), Last Minute Risk Assessment (LMRA), and Lock Out Tag Out (LOTO) procedures,
- HSE post-evaluation phase – monitoring of KPIs and formal HSE assessment of contractors.

This structured approach enables identification of critical control points and evaluation of risk management effectiveness throughout the maintenance lifecycle.

The research is based on a qualitative case-study analysis of the INA Group contractor management framework and maintenance management system. The analysis included internal HSE procedures, maintenance management processes, contractor performance monitoring requirements, and HSE performance indicators to provide a comprehensive understanding of the existing framework and identify opportunities for improvement.

3. CONTRACTOR MANAGEMENT AND HSE FRAMEWORK

CM represents a structured approach to controlling risks associated with outsourced activities [1]. It ensures that all contractors and subcontractors comply with defined HSE standards throughout the entire lifecycle of contracted work. Key elements of CM include:

- **Risk assessment processes**, including Preliminary Risk Assessment and task-specific hazard analysis
- **Permit to Work (PTW) system**, ensuring controlled execution of high-risk activities [7]
- **Job Safety Analysis (JSA) and Last-Minute Risk Assessment (LMRA)**, enabling dynamic risk identification [8]
- **Lock Out Tag Out (LOTO)** procedures for energy isolation [8]
- **Mandatory HSE training and onboarding requirements** [1]

These elements provide a systematic framework that ensures hazards are identified, risks are controlled, and responsibilities are clearly defined before and during the execution of maintenance activities. An important aspect of CM is the classification of work based on risk level (low, medium, high), which determines the level of control, supervision, and documentation required.

4. INTEGRATION OF CM, SAP PM/SM AND THE SSC MODEL

The SAP PM system plays a central role in organizing and controlling maintenance activities within the INA Group by enabling standardized planning, scheduling, and execution through structured work orders and integrated equipment data [13]. It supports key functionalities such as work order management, prioritization based on operational needs and risk, integration with technical documentation, and tracking of maintenance history and performance indicators, ensuring alignment with organizational priorities and HSE requirements. In parallel, the SAP SM module extends this framework by supporting service-oriented and contractor-related activities, including the management of service requests, execution, and performance tracking. This integration strengthens coordination between internal maintenance teams and external service providers, ensuring a

consistent and controlled approach to maintenance execution. Together, these modules provide full traceability, enforce standardized procedures, and significantly reduce the risk of uncontrolled or unsafe work activities.

Within this operational framework, the SSC model represents a centralized approach to maintenance execution, where the SSC acts both as:

- The **main contractor performing maintenance activities**, and
- The **manager of subcontractors involved in execution.**

This dual role significantly increases the importance of integration between Contractor Management and SAP based maintenance systems. The SSC model enables standardization of procedures, centralized supervision, and improved communication between operational and HSE teams. However, it also introduces additional complexity in terms of accountability and risk management, particularly when multiple subcontractors are involved. Therefore, strict adherence to CM processes and HSE requirements is essential.

Table 1: Comparison of SSC Model, HSE requirements and SAP PM/SM System

Aspect	SSC Model (Single Service Company)	HSE requirements	SAP PM/SM System (Plant Maintenance)
Primary Function	Execution and coordination of maintenance activities	Certification of contractor HSE management systems	Planning, scheduling and documentation of maintenance activities
Role in Maintenance	Acts as main contractor and subcontractor coordinator	Ensures contractor competence and safety compliance	Defines work orders, priorities and resource allocation
Focus Area	Operational execution and on-site supervision	HSE management system	Technical and operational workflow management
Responsibility	Implementation of maintenance activities and HSE measures	Compliance with international safety standards	Structuring and tracking maintenance processes
Risk Management	Application of PTW, LOTO, JSA and LMRA procedures	Requires formal risk management systems and audits	Integrates risk considerations into maintenance planning
Contractor Control	Direct supervision and coordination of subcontractors	Prequalification and certification of contractors	Assignment of qualified contractors to tasks
Standardization Level	High – unified procedures across operations	High – standardized certification requirements	High – standardized workflows and documentation
HSE Integration	Practical implementation of HSE measures on site	Formal verification of HSE system effectiveness	Integration of HSE requirements into planning phase
Supervision	Continuous supervision during execution	Periodic audits and certification checks	Monitoring through system tracking and reporting
Performance Monitoring	KPIs monitoring and HSE post-evaluation	Audit results and certification validity	Maintenance KPIs and historical data tracking
Key Contribution	Ensures safe and efficient work execution	Ensures contractor competence and compliance	Ensures structured, traceable and optimized maintenance
Limitations	Requires strong coordination and clear accountability	Certification does not guarantee on-site behaviour	Does not control execution without CM integration

Source: Authors' elaboration based on INA Group HSE0445, INA HSE Appendix to Contract and SAP PM/SM maintenance management framework [1–3].

The integration of the SSC model, Safety Certificate Contractors (SCC/SCC_P) certification, and SAP PM system represent a key element in achieving effective maintenance and HSE management. Table 1 provides a comparative overview of these components and their roles within the integrated framework. As shown in Table 1, each system has a distinct but complementary function. The SSC model focuses on execution and coordination, SCC/SCC_P certification ensures contractor competence and HSE compliance, while SAP PM provides structured planning and traceability of maintenance activities. Their integration enables a comprehensive approach to both operational and safety management. In the context of the INA Group, the requirement for SCC_P certification, particularly for high-risk maintenance activities, ensures that contractors entering the system already possess a defined level of HSE maturity. When combined with CM processes, SAP PM planning, and SSC-based supervision, this creates a robust framework that not only enforces compliance but actively promotes the development of a proactive and integrated safety culture.

5. PERFORMANCE MONITORING AND CONTINUOUS IMPROVEMENT

Continuous monitoring of contractor performance and safety indicators is essential for maintaining high HSE standards. In the INA Group, this is achieved through:

- **KPIs**, including safety metrics and compliance indicators
- **HSE post-evaluation procedures**, assessing contractor performance after completion of works
- **Analysis of incidents, near misses, and rule violations**
- **Implementation of corrective actions and improvement measures**

HSE post-evaluation results are used to:

- Improve contractor selection processes
- Enhance training and supervision practices
- Strengthen risk management strategies

This feedback loop ensures continuous improvement and supports the development of a proactive safety culture.

“Good safety is good business” is a common mantra. But how do we quantify the value that good safety performance brings? A common method is to measure of accidents that occur. There have been many calculations done which tell us that each Lost-time Injuries (LTI) cost somewhere between $27,000 and $34,000. Thirty fewer LTIs means saved almost $1.3 million [9].

The Bradley Curve is a widely used safety culture maturity model in industrial HSE management, developed within DuPont in the mid - 1990s. It describes the evolution of organisational safety culture through four stages: Reactive, Dependent, Independent, and Interdependent. The model is based on the idea that stronger safety culture and more mature behavioural safety practices are associated with better safety performance and fewer incidents. In the Reactive stage, safety is generally managed only after incidents occur, with limited organisational ownership. The Dependent stage is characterised by rule-based compliance and supervisory control, where employees follow

procedures primarily because management requires it. In the Independent stage, employees take personal responsibility for safe behaviour. The Interdependent stage represents the highest level of maturity, where safety becomes a collective organisational value supported by mutual accountability, peer intervention, proactive reporting, and continuous improvement [4,5].

Based on publicly available HSE performance data in sustainability reports [6], INA Group can be conservatively positioned at the boundary between the Independent and Interdependent stages of the Bradley Curve, where safety is embedded in processes, planning, and contractor management. This maturity level enables effective risk control, shared responsibility, and continuous improvement of HSE performance.

HSE performance data of the INA Group were compared with relevant industry benchmarks. For downstream operations, reference data published by CONCAWE were used, while upstream activities were evaluated against performance indicators reported by the International Association of Oil & Gas Producers (IOGP). Such benchmarking enables objective assessment of safety performance within the context of the oil and gas industry [10,12]

Figure 1 presents the position of the INA Group on the Bradley Curve. The primary indicator for worker health and safety management is the Total Recordable Injury Rate (TRIR). This metric represents the number of Total Recordable Injuries (TRI) per 1 million hours worked, i.e. TRIR = TRI * 1,000,000/total hours worked. TRI includes Lost-time Injuries (LTI), Restricted Workday Cases (RWC), Medical Treatment Cases (MTC) and includes both INA Group employees and contractors. TRIR is constantly monitored, for 2025, the INA Group level tolerable TRIR limit was set at 1.63, and the final rate was met, with the actual TRIR being 1.24 (last point on curve). Considering data from previous years, where the TRIR decreased from 1.58 in 2023 to 1.54 in 2024 and further to 1.24 in 2025, a clear and continuous downward trend in the injury rate can be observed. The comparison showed that INA Group safety performance indicators are within the range reported by leading industry organizations and demonstrate a positive trend in occupational safety performance [6,10,12].

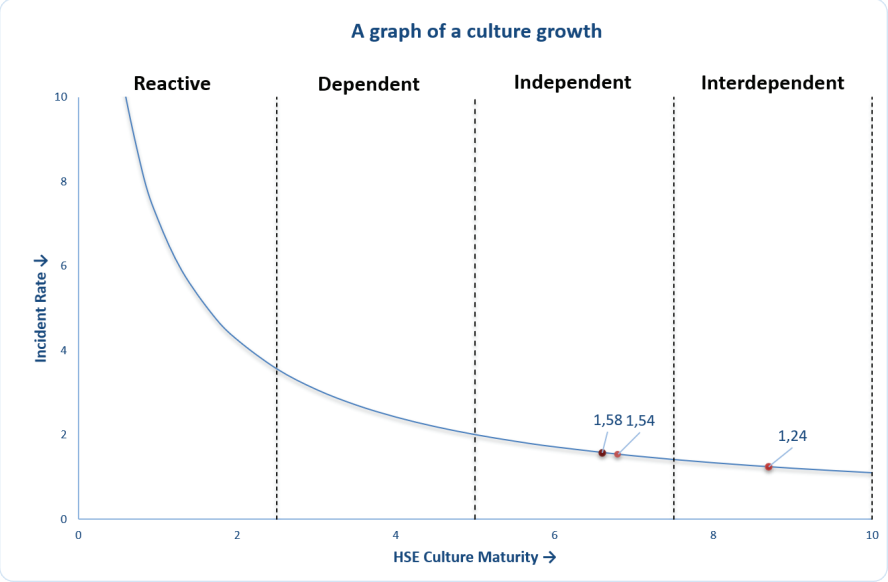


Figure 1: HSE Culture Development Based on the Bradley Curve [4] with INA Group Position

Figure 1 indicates a transition towards a proactive and interdependent HSE culture, characterized by systematic risk management, strong integration of HSE requirements, and shared responsibility among stakeholders. This positioning reflects a mature HSE system where safety is integrated into operational processes rather than treated as a separate compliance requirement. The presented model represents a scalable and transferable framework for improving HSE performance in complex industrial environments.

6. DISCUSSION

The results of this paper demonstrate that the systematic integration of defined minimum HSE requirements across all phases of the contractor management process has a significant impact on improving safety performance and strengthening risk control in maintenance activities.

In relation to **RQ1**, the analysis shows that the effective communication of hazards during the tendering phase, particularly through preliminary risk assessments, represents a critical starting point for risk management. Early identification and transparent communication of hazards enable contractors and subcontractors to better understand the scope of risks and prepare appropriate control measures before entering the work environment [5,15].

Regarding **RQ2**, the findings indicate that the structured definition of HSE criteria and expectations during the contracting phase ensures alignment between risk levels and required safety measures. By linking HSE requirements directly to identified hazards and risk categories, organizations can establish clear expectations and reduce ambiguity in contractor obligations [11].

In terms of **RQ3**, the paper confirms that defining certification requirements based on risk levels, including SCC/SCC_P certification for high-risk activities, significantly contributes to ensuring contractor competence and standardization of safety practices. This approach provides an additional level of risk control by ensuring that only qualified contractors are engaged in critical maintenance activities [5,11].

With respect to **RQ4**, the analysis highlights that clearly defined sanctioning mechanisms for non-compliance with HSE rules play an important role in enforcing safety standards. The combination of contractual penalties, performance evaluation, and exclusion criteria reinforces accountability and encourages adherence to safety requirements [5].

The role of the SSC model, addressed in **RQ5**, proves to be essential in bridging the gap between planning and execution. The SSC model enables centralized coordination and supervision of maintenance activities, ensuring consistent implementation of HSE requirements and facilitating communication between operational and safety functions [10].

Finally, in relation to **RQ6**, the paper demonstrates that KPIs monitoring and HSE post-evaluation processes provide an effective mechanism for continuous improvement. The feedback loop created through performance measurement and evaluation enables organizations to identify weaknesses, implement corrective measures, and continuously enhance safety performance [11].

Overall, the integration of Contractor Management, SAP PM, and the SSC model create a comprehensive system in which safety and operational efficiency are managed simultaneously. The inclusion of structured HSE controls throughout the process lifecycle ensures that risks are systematically identified, evaluated, and controlled.

These findings are consistent with contemporary research on safety culture development, contractor management, and performance-based HSE systems, which highlight the importance of integrating organizational, technical, and behavioural safety controls to achieve sustainable improvements in safety performance [5,10,11].

7. CONCLUSION

This paper has analysed the role of defined minimum HSE requirements in managing particularly hazardous maintenance activities within the INA Group. The findings confirm that the integration of HSE requirements across all phases of the contractor management process—tendering, contracting, execution, and HSE post-evaluation—significantly contributes to improved safety performance, enhanced risk control, and more efficient maintenance execution.

The SSC model plays a critical role in operationalizing these requirements by ensuring consistent implementation, supervision, and coordination of contractors and subcontractors. In combination with SAP PM, which provides structured planning and traceability, this integrated system enables effective management of both operational and safety aspects.

Based on available evidence, INA Group demonstrates many characteristics associated with advanced HSE culture maturity, particularly through systematic risk management, integration of HSE requirements into operational processes, proactive safety initiatives, and increasing levels of shared responsibility among employees, contractors, and management. Consequently, INA Group can reasonably be positioned between the Independent and Interdependent stages of the Bradley Curve, reflecting a mature HSE system focused on continuous improvement and proactive safety culture development.

Building on the findings of Khordoustan et al. (2026) [14] and findings of this study, organizations operating in high-risk industries should further strengthen the integration of contractor management systems and digital maintenance management platforms. Additional improvements may be achieved through real-time monitoring technologies, enhanced contractor competency verification, predictive risk management tools, and continuous development of safety culture programmes. Future research should move beyond traditional lagging indicators and investigate the effectiveness of leading indicators as predictors of contractor HSE performance. Attention should be given to identifying which proactive safety metrics are most strongly associated with incident prevention and long-term improvements in contractor safety outcomes.

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Professional paper

SAFETY ANALYSIS OF AN INCIDENT THAT OCCURRED DURING DISMANTLING OF STEAM SUPPLY PIPE

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Abstract: *During production or maintenance processes in industrial plants, it is mandatory to adhere to all protective measures and all safety standards. Inadequate safety standards, lack of protective equipment and lack of preventive measures and risk analysis lead to higher possibility of incident or an accident with fatal consequence. Therefore, before any kind of production process, it is necessary to prescribe procedure for completing a specific work task and to create a plan for implementation of safety measures designed to minimize or eliminate potential risks during work activities. But, despite all the safety measures that should be taken before work activities, an incident or accident can happen anyway. An incident occurred in steel factory in Germany during dismantling of steam supply pipe will be analyzed and presented in this article. The incident occurred due to incomplete method statement for planned work activity, which consequently led to a violation of worker safety and damage to the piping system.*

Keywords: *pipe dismantling, safety standards and measures, method statement*

1. INTRODUCTION

Each work activity and related occupational safety are primarily subject to the Occupational Safety and Health Act [1] of the country where the industrial facility is located. Furthermore, there are occupational safety rules of the facility [2] itself where the work activity takes place. And finally, dismantling of steam supply pipe, as a work activity which will be presented in this article, must be prepared and performed according to applicable construction and engineering standards [3] and regulations [4].

2. METHOD STATEMENT AND DISMANTLING PROCEDURE

Under the Construction (Design and Management) Regulations [4] construction phase plan [4,5] is mandatory for every construction activity, also for dismantling of piping system. Construction phase plan is the document prepared to manage and monitor work activity so it can be carried out in a way that secures health and safety.

This document is followed by a method statement [3,4] as crucial document which prescribes procedure for completing a specific work task. Method statements are commonly used in construction, engineering, manufacturing and high-risk industries, where detail planned and risk management are obligatory. It defines sequence of operations of work activity while ensuring safety, quality and compliance with regulations. Also, if the company follows and prepares comprehensive method statement, they fulfill requirements of international management standard ISO 9001 [6]. This standard recommends that employees should be trained to perform their work activities and site work instructions must be displayed at place of work.

Components for a typical method statement are presented in Table 1 [4,7].

Table 1: Key Components of a Method Statement

Component for method statement	Description
General information about the project	Company, location, Project/Task number
Project / Task description	Brief description of the task and its expected duration. Definition of roles and responsibilities
Sequence of Work	Detailed procedure and step-by-step instructions for the task including QA/QC requirements and monitoring
Equipment and Materials	List of equipment, tools and materials required to perform the work
Safety precautions	Definition of risks, hazards, PPE and control measures. Emergency procedures.

Major component for dismantling of steam supply pipe is detailed task procedure [3,8] which must contain following:

- Ensuring that the pipe is not in operation and is depressurized
- Determination of access to pipe and definition of cutting locations. Erect scaffolding [9] or use man-lifts for working at height.
- Review of piping isometric drawing with the purpose to locate supports, valves, fittings, compensators…etc. nearby cutting locations or on the pipe sections which will be removed or will remain
- Performing pipe stress analysis to check stability and prevent uncontrolled movements of pipe sections which remain on its location after cutting. If necessary, design and install temporary supports to ensure stability.
- Lifting and removal plans. Determination of hanging points and applicable lifting tools and equipment.
- Removing the insulation, if exists. Loosening of supports and connections to steelwork.
- Cutting sequence and selection of cutting tools. Using cold cutting tools or hot works if it is safe and permitted.
- Moving dismantled materials to a designated area.

3. GENERAL DATA ABOUT THE PIPE AND DESCRIPTON OF THE INCIDENT

Steam supply pipe, presented in this article, distributes pressurized steam from boilers to several equipment and is used for various production processes within the steel factory.

Pipe is designed with nominal diameter of DN500, works on design parameters of 325°C and 10 bars, made of P235GH material and is insulated. The pipe is periodically checked and, according to a previously established plan, individual sections are replaced with new ones.

Part of piping isometric [10], presented on Figure 1, shows cutting points and pipe section, approximately 25 meters long, which was planned for dismantling and replacement. That section is located on pipe rack at height of 12 meters above the ground level.

Thus, the work activity is more complicated and dangerous because it involves working at height, different types of protective equipment, additional scaffolding and special lifting equipment.

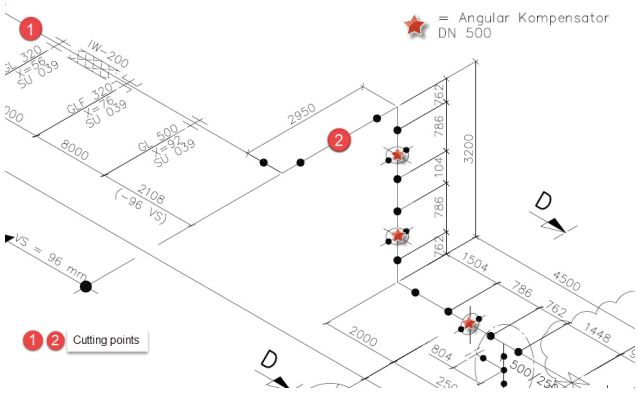


Figure 1: Piping isometric, cutting points and angular compensators [10]

Pipe was cut at marked points in a previously determined sequence, point 1 and then point 2. After cutting at point 2, the remaining part fell uncontrollably and got stuck on the scaffolding and the existing steel structure, as presented in Figure 2. Fortunately, despite a very dangerous event, none of the staff were injured.



Figure 2: Position of remaining part after cutting [11]

Afterwards, dismantled pipe section was lifted with lifting equipment and moved to designated area.



Figure 3: Lifting and removal of dismantled pipe section [11]

4. ROOT CAUSE ANALYSIS AND DETERMINATION OF DISMANTLING PROCEDURE VIOLATION

Immediately after the incident occurred, root cause analysis [11] was carried out to determine which phases of dismantling procedure have not been performed correctly or have been omitted and missed.

Investigation revealed several major omissions in dismantling procedure which are documented in an internal report [11].

a) Piping isometric drawing was not correctly reviewed. Three compensators on remaining part were not detected as the most elastic elements in the system which require additional supporting or reinforcement before cutting.
b) Pipe stress analysis was not requested and therefore was not performed to simulate the behavior of the remaining pipeline after cutting.
c) Because of all the above, temporary supports were not installed to ensure stability and prevent uncontrolled movements.
d) Lack of correspondence between maintenance staff and engineering department.
e) Organizational structure with defined responsibilities was incomplete

Consequently, after the insulation was removed, it was discovered that one of the compensators had suffered significant angular deformation of about 8.8°. Deformation, as well as measured value, are shown in Figure 4. It was also determined that the deformation was mainly caused because this compensator took over most of the weight of the remaining part of the pipe.

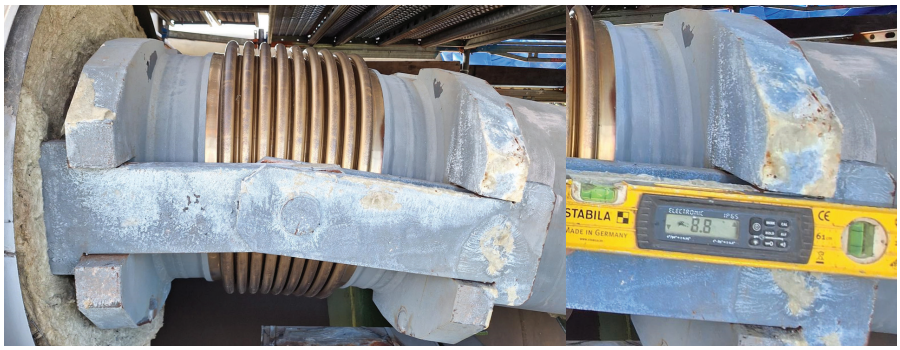


Figure 4: Angular deformation of the compensator [11]

5. PIPE STRESS CALCULATION AND ADDITIONAL EXAMINATION

Considering the facts from root cause analysis, pipe stress calculation [12] was performed to check

compensator deformation and stresses in system caused by this deformation. An additional goal of the calculation was to simulate the behavior of the remaining pipe after cutting.

As it is shown in Figure 5. calculated compensator angular deformation is 10° which confirms the accuracy of the measured value. Calculated stress is negligible.

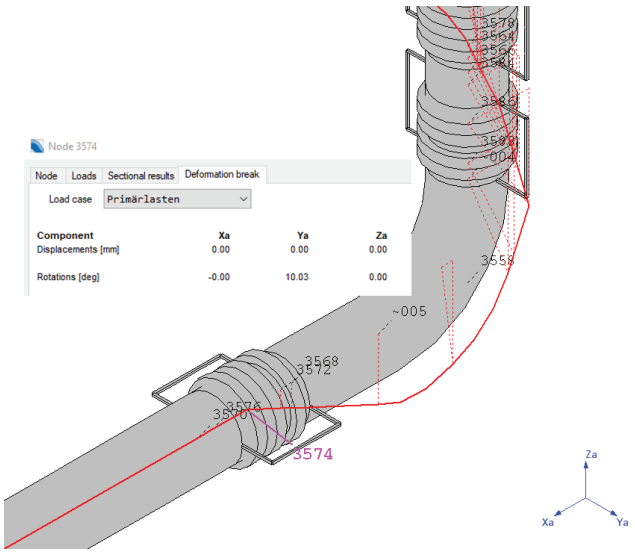


Figure 5: Calculated compensator angular deformation [12]

Despite the fact that both values, measured and calculated, are lower than allowable angular deformation of 13,5° according to manufacturer's documentation [13], a mandatory radiographic examination and penetrant testing were performed on compensator bellows and welds at the connections with pipe.

There was no evidence of cracks or similar damage. Therefore, it was not necessary to replace that part of the pipeline as well as the compensator.

6. CORRECTIVE MEASURES AND UPDATE OF WORK INSTRUCTIONS

After detailed review of root cause analysis, corrective measures were issued for future similar or identical pipeline dismantling work activities. Furthermore, already existing work instructions were updated. The most important items are as follows:

a) Method statement and dismantling procedure must be prepared and reviewed in more precise and detailed manner.
b) The organizational structure must be respected, especially for the work activity control phase.
c) Piping isometrics, support drawings and steel structure design must be reviewed in coordination between maintenance staff and engineering department.
d) Final decision to perform pipe stress calculation and the necessity for implementation of additional temporary supports should be made by the engineering department.

7. CONCLUSION

The incident presented in this article is an obvious example when negligence or omissions in work procedures can lead to unwanted and fatal consequences for worker safety and damage to environment and facilities. In this specific case, fortunately, no one was injured and no significant damage was found to the pipeline and the surrounding steel structure.

But additional work capacities were spent on determining the cause of the incident and defining improvements in the preparation and execution of the work activity, all with the purpose of preventing something similar would not happen again. Likewise, all work activities have been stopped for several days until the root cause analysis process is completed. All of this was indicated as an unnecessary financial expense that could be avoided if everything had been performed according to rules and procedures.

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Professional paper

NEAR-MISS REPORTING, INTERNAL AUDIT AND MANAGEMENT REVIEW: AN INTEGRATED SAFETY MANAGEMENT MODEL

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Abstract: *Near-miss events provide organisations with information about hazards and control weaknesses before injury, fire, property damage or operational interruption occurs. This professional and conceptual paper proposes an integrated model linking near-miss reporting with potential-severity classification, root-cause analysis, corrective action, internal audit verification and management review. Based on ISO 45001, ISO 19011 and a structured synthesis of literature on near-miss management, safety culture and leading indicators, the paper explains the role of near-miss systems in injury prevention, presents a risk-based audit and management-review model with an illustrative full-cycle case, and discusses their potential financial, reputational and ESG relevance for employers. Supporting audit questions, KPIs and a five-level maturity path are presented. The model is not empirically validated; claimed benefits should therefore be evaluated through organisation-specific implementation data.*

Keywords: *near miss, near-miss reporting, occupational safety and health, fire safety, internal audit, leading indicators*

1. INTRODUCTION

Occupational safety and health (OSH) management is increasingly expected to move beyond formal compliance and retrospective injury statistics towards proactive identification of weak signals, worker participation and continuous improvement. ISO 45001 treats an incident broadly enough to include occurrences that could have resulted in injury or ill health, which provides a management basis for learning from near misses as well as from events with actual consequences [1]. The value of near-miss information has also been recognised in process industries, construction and broader industrial research, where structured reporting and analysis are used to identify precursors and weaknesses before escalation [2–4].

A near miss is an unplanned event or condition that caused no injury, illness, fire, environmental release, property damage or business interruption, but had the potential to do so. Examples include a near collision between a forklift and a pedestrian, a falling object that misses a worker, smoke from an electrical cabinet without ignition, a blocked evacuation route, failure of machine guarding without

injury, or work at height where a fall is avoided by chance. These events are operational evidence that a control barrier was absent, weak or challenged.

Near-miss reporting is not effective merely because reports are collected. Literature on near-miss management emphasises the importance of a complete management cycle that includes reporting, analysis, action and organisational learning [2,3]. Recent evidence also indicates that employees' perception of how the organisation responds to reported near misses matters: inadequate or absent organisational response can weaken trust and the safety climate [5]. This makes feedback and visible corrective action central components of a credible reporting system.

The continuing scale of work-related harm provides a strong reason to complement lagging indicators with proactive information. The International Labour Organization estimates approximately 2.93 million work-related deaths and 395 million non-fatal occupational injuries annually [10]. Eurostat reported 2.83 million non-fatal accidents at work and 3,298 fatal accidents in the EU in 2023 [11]. In Croatia, the Croatian Health Insurance Fund received 17,240 occupational-injury reports in 2023, of which 13,419 had been recognised by 31 March 2024 [12]. These figures describe outcomes after harm has occurred; near-miss data can support earlier intervention when used as part of a wider safety-management system.

2. NEAR MISS: CONCEPT, ROLE AND ORGANISATIONAL VALUE

The term near miss is used in this paper for the event itself, while near-miss reporting, near-miss system and near-miss data are used as compound terms. Standardised terminology is important because inconsistent definitions can reduce reporting quality and comparability. Reviews of industrial near-miss management systems show that no single universal implementation method exists, but recurring elements include event capture, classification, analysis, corrective action, feedback and dissemination of learning [2].

Near-miss reporting has three principal organisational roles. First, it converts everyday observations into structured information on where barriers are being challenged. Second, it supports worker participation by creating a channel through which employees and contractors can identify risk conditions that may not be visible in formal documentation. Third, it provides potential leading information for management. Research on OSH leading indicators stresses that proactive measures are most useful when they are actionable and connected with management commitment and follow-up [6,7]. Near misses should therefore not be interpreted as a simple count; their value depends on potential severity, quality of analysis, speed of response, action closure and recurrence.

Reporting behaviour is strongly influenced by organisational culture. Workers may not report because they fear blame, believe that 'nothing happened', find the process complicated or have learned that previous reports produced no visible response. Studies of near-miss reporting and safety climate support the importance of a learning-oriented, non-punitive response and timely feedback [5,9]. For this reason, an initial increase in near-miss reports can indicate improved recognition and trust rather than deteriorating safety. Conversely, a low report count cannot by itself demonstrate a safe workplace.

Near-miss management should also include fire safety and contractor activities. Overheated electrical equipment, blocked exits, unavailable extinguishers, open fire doors, uncontrolled hot work, flammable materials near ignition sources and gas releases without ignition are examples of weak signals that can be captured before a fire develops. The same reporting and verification logic can therefore support OSH, fire protection, maintenance, contractor control and business continuity.

3. METHODOLOGICAL APPROACH

This paper is a professional and conceptual contribution rather than empirical research. The proposed model was developed through a structured synthesis of four sources: (i) ISO 45001 requirements and guidance related to incidents, worker participation, corrective action and management review [1]; (ii) ISO 19011:2026 guidance on evidence-based and risk-based auditing [13]; (iii) academic literature on near-miss management, safety culture and leading indicators [2–9]; and (iv) recurring OSH and fire-safety control domains encountered in professional audit and review practice.

The audit questions were derived by mapping recurrent control domains to the types of information that near-miss reports can reveal. The KPI set was selected to balance reporting activity, potential consequence, response speed, corrective-action closure, recurrence and worker participation. The maturity path was constructed as a five-level conceptual progression from formal compliance to integrated risk management. The framework has not been statistically validated and should be adapted to the size, sector and risk profile of the organisation before empirical evaluation.

4. WHY NEAR-MISS SYSTEMS MATTER FOR INJURY REDUCTION

Near-miss information is valuable because it reveals hazardous interactions and control failures before they produce injury. Accident-pyramid models can help communicate the idea that serious outcomes are often preceded by a wider base of weak signals, but they should not be treated as fixed mathematical ratios or as proof that a specific number of reports will prevent an injury. The preventive value lies in using each credible signal to identify where risk is active and where barriers require strengthening [2–4].

Risk reduction occurs only when reporting is connected with potential-severity assessment, root-cause analysis, corrective action, verification of effectiveness and review of the risk assessment. In that sense, near-miss data function as leading information: they allow an organisation to intervene before harm rather than measuring performance only after an accident has occurred [6–8]. Reporting without response may create distrust, while corrective action without verification can create a false sense of closure. The illustrative internal-transport case in Section 6 demonstrates how this full cycle can be applied in practice.

5. INTEGRATED NEAR-MISS, AUDIT AND MANAGEMENT-REVIEW MODEL

The proposed model treats a near miss as an early signal and internal audit as the mechanism that verifies whether the organisation has responded effectively to that signal. The core cycle is: near-miss report → potential-severity classification → root-cause analysis → corrective or preventive action → audit verification → system review → management decision. Reporting without response creates distrust; analysis without action creates formalism; and action without verification may create a false sense of closure.

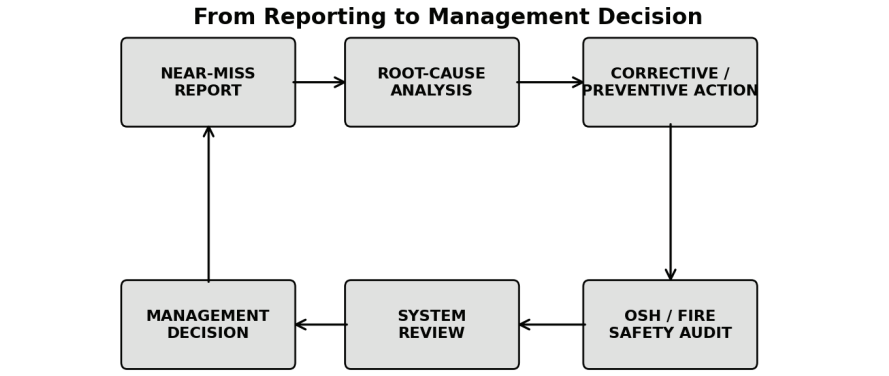


Figure 1: Integrated near-miss, audit and management-review cycle

The audit programme should be risk-based. Repeated or high-potential near misses should influence audit priorities because they indicate where controls are being challenged in real work. ISO 19011:2026 reinforces evidence-based and risk-based approaches to auditing [13]. Audit verification should therefore move beyond documentation and examine whether controls operate in practice, whether corrective actions address root causes and whether equivalent risks exist at other locations or organisational units.

Table 1: Risk-based audit questions linked to near-miss data

Audit area	Core question	Use of near-miss data
Risk assessment	Does the assessment reflect recent work changes and reported weak signals?	Repeated near misses may indicate missing or underestimated hazards.
Work equipment	Are guards, protective devices, maintenance and inspections effective in practice?	Equipment-related reports help target verification.
Internal transport	Are pedestrian and vehicle routes adequately separated and controlled?	Near collisions identify high-priority traffic risks.
Fire protection	Are exits, fire doors, extinguishers, alarms and hot-work controls functional?	Fire-related weak signals become direct audit inputs.
Contractors	Are contractors included in induction, supervision and reporting arrangements?	Contractor near misses can reveal interface and communication gaps.
Corrective actions	Are actions closed on time and verified for effectiveness?	Closure quality determines whether recurrence is reduced.
Management review	Does management receive trends, high-potential events and overdue actions?	Aggregated data support risk-based allocation of resources.

6. PRACTICAL APPLICATION: ILLUSTRATIVE CASE

The following example is an illustrative professional scenario and is not presented as empirical study data. It demonstrates how the proposed cycle can be applied to a common internal-transport event.

Table 2: Full near-miss cycle – illustrative forklift/pedestrian case

Stage	Illustrative case	Management purpose
1. Report	A forklift exits a blind aisle while a pedestrian enters the shared route; emergency braking prevents contact.	Record location, time, persons involved, task and immediate conditions.
2. Classification	Potential consequence: serious injury or fatality; category: internal transport; high-potential near miss.	Escalate for prompt analysis and management visibility.
3. Root-cause analysis	Shared traffic route, poor visibility, temporary storage near the corner, inadequate physical separation and inconsistent speed control.	Focus on system conditions rather than individual blame.
4. Corrective action	Remove visual obstruction; install physical pedestrian separation and a defined crossing; improve mirror/signage and speed control; refresh driver and contractor briefing.	Assign responsible persons and deadlines; update risk assessment.
5. Audit verification	Verify barriers and route markings on site, observe real traffic behaviour, check training/induction records and review any repeated reports.	Close the action only when implementation and effectiveness are evidenced.
6. Management review	Compare similar layouts across sites, review internal-transport KPI trends and decide whether wider investment or standardisation is required.	Convert a local warning into organisational learning and resource decisions.

7. FINANCIAL, REPUTATIONAL AND ESG BENEFITS FOR EMPLOYERS

The financial relevance of near-miss management is primarily preventive. Injuries, fires and equipment incidents can generate direct costs such as medical treatment, compensation and repair, as well as indirect costs through downtime, replacement labour, overtime, investigation, delayed delivery and management disruption. EU-OSHA materials therefore frame effective OSH management as relevant to business performance and prevention economics [16]. A near-miss system does not guarantee a measurable return on investment, but timely corrective action can reduce exposure to events that may produce substantially greater losses.

Reputational value should likewise be understood as risk reduction and evidence of responsible management rather than as an automatic improvement in corporate image. A documented reporting, investigation and audit trail can demonstrate to clients, insurers, parent companies and other stakeholders that safety concerns are identified, escalated and closed. This can support credibility during supplier assessments and due-diligence processes, while repeated unresolved events or weak corrective-action control may create operational and reputational risk. OECD due-diligence guidance reinforces the need to identify, prevent and mitigate actual and potential adverse impacts in operations and business relationships [15].

In the ESG context, occupational health and safety is part of the social dimension. ESRS S1 includes health-and-safety disclosures and metrics concerning management-system coverage, work-related accidents, fatalities and days lost, together with information relevant to how such systems are managed and reviewed [14]. Near-miss reporting is not a substitute for these required outcome

metrics; rather, it can complement them by providing leading evidence of hazard identification, worker participation, corrective action and internal verification. For employers, the combined benefit is a more auditable basis for prevention, management review and stakeholder communication, while claims about improved competitiveness or resilience should remain proportionate to organisation-specific evidence.

8. KPIs AND MATURITY PATH

A near-miss system should not be evaluated only by the total number of reports. Near misses can have both leading and lagging characteristics depending on how the information is used, and safety-performance literature recommends combining activity measures with indicators that show the effectiveness of preventive processes [6–8]. The KPI set should therefore show whether employees use the system, whether high-potential events are identified, how quickly actions are closed and whether the same root causes recur.

The maturity path translates the conceptual model into a practical progression that can be used during internal review. It is intended to show how reporting, verification and management use of safety information can evolve, rather than to assign a universal score to an organisation. Progress may differ between locations, departments and risk domains, and evidence should therefore be assessed separately for the areas under review.

Table 3: Suggested near-miss and audit-related KPIs

Indicator	What it shows	Interpretation
Near-miss reports per 100 workers	Reporting activity and participation	Interpret together with culture and exposure; more reports are not automatically worse performance.
Share of high-potential near misses	Potential severity profile	Supports prioritisation of serious risk.
Average corrective-action closure time	Speed of organisational response	Highlights delayed risk reduction.
Actions closed on time and verified	Implementation discipline and audit effectiveness	Distinguishes administrative closure from verified effectiveness.
Repeated root causes / repeated event types	Learning effectiveness	Signals unresolved systemic weaknesses.
Share of worker/contractor reports	Participation and reporting trust	Shows whether reporting reaches beyond the safety department.

Table 4: Conceptual safety-system maturity path

Level	Operational characteristic	Typical evidence
1. Formal compliance	Documentation, training and inspections are available, but the system is mainly activated after accidents, fires or inspections.	Basic records, legal compliance checks and reactive corrective actions.
2. Reactive management	Incidents and identified deficiencies trigger investigation and corrective action, but weak signals are not yet systematically captured.	Incident investigations, action lists and periodic management follow-up.
3. Near-miss culture	Workers and contractors routinely report weak signals and receive visible feedback; high-potential events are classified and analysed.	Near-miss records, reporter feedback, root-cause analyses and trend reports.
4. Audited system	Near-miss trends and corrective actions influence risk-based audit planning, and implementation is verified on site.	Audit trails, effectiveness checks, overdue-action control and cross-site verification.

Level	Operational characteristic	Typical evidence
5. Integrated risk management	Safety information is used in management review, investment prioritisation, ESG-related disclosures and relevant supply-chain decisions.	Management-review inputs, KPI dashboards, resource decisions and documented organisational learning.

A practical maturity review should focus on evidence of behaviour and control effectiveness, not on the presence of documents alone. For example, progression from Level 3 to Level 4 requires evidence that repeated or high-potential near misses actually change audit priorities and that corrective actions are verified for effectiveness. Progression to Level 5 requires evidence that aggregated safety information reaches management review and influences resources, standards or wider organisational decisions. The maturity path can therefore be used as a discussion framework during internal audits and management reviews, while organisation-specific criteria should be defined before any formal scoring is introduced.

9. DISCUSSION

The central implementation challenge is cultural rather than technical. A simple digital form or QR code may facilitate reporting, but it does not create a learning system unless workers trust the process, supervisors respond fairly and management closes the feedback loop. Recent literature consistently identifies management involvement, employee training, reporting climate and organisational response as important conditions for effective near-miss systems [2,5,9]. This supports a shift from measuring how many reports were collected to evaluating how effectively the organisation responds to them.

The proposed framework also connects near-miss information with internal audit in a more operational way. Near-miss reports identify where risk has appeared; audit verifies whether the intended controls and corrective actions function in practice; management review evaluates trends, recurrence and cross-site significance; and management decisions allocate resources or revise standards. This cycle helps prevent near-miss reporting from becoming an isolated administrative database.

Several limitations should be recognised. The paper does not present empirical testing, causal estimates or quantified financial effects. The illustrative case demonstrates application logic but does not constitute evidence of outcome improvement. Sector-specific hazards, legal requirements and reporting cultures will influence the design of the system and the selection of KPIs. Future work should test the proposed model using longitudinal organisational data, including reporting rates, high-potential-event trends, corrective-action closure, recurrence, audit findings and injury or fire outcomes.

For implementation, organisations should begin with a limited number of clearly defined reporting categories and responsibilities, then expand the system only after the reporting-feedback loop is functioning. High-potential events should receive priority regardless of frequency, while recurring lower-severity events should be reviewed for common causes. Audit programmes can then use these patterns to select sites, processes or contractor interfaces for verification. This staged approach keeps the reporting process proportionate and helps ensure that data collection remains connected with corrective action and management decisions.

10. CONCLUSION

Near-miss reporting is most valuable when it enables action before harm occurs. Integrating reporting with potential-severity classification, root-cause analysis, corrective action, audit verification and management review provides a practical structure for converting weak signals into organisational learning. Used in this way, the system can support earlier identification of conditions that may lead to injury, while also strengthening control of potential financial loss, business interruption and fire-related events. A documented reporting and verification trail can additionally provide auditable evidence for management review, client or supplier assessments and ESG-related safety governance. These are potential benefits, not guaranteed outcomes; the paper does not claim quantified effects on injury rates or business performance.

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Original scientific paper

ASSESSMENT OF TREE VITALITY FOR PEDESTRIAN SAFETY: A CASE STUDY OF ADŽIJA SQUARE IN KARLOVAC

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Abstract: *Increasing temperatures and increasing the intensity of urban heating synergistically lead to a decrease in tree immunity and ultimately to the cracking of parts or entire trees, attacks by fungal diseases and insects. Urban areas in populated areas that are enriched with green areas, gardens and parks thus become places of potential danger for passers-by and their property. The aim of this paper was to examine a city square in the historic city center of Karlovac where tree plantations were established. For the purposes of this paper, the resistograph and VTA methods were used to analyze the health of trees. The conclusion describes tree care guidelines and the possible renovation of the Square.*

Keywords: *arboriculture, urban forestry, tree vitality, safety*

1. INTRODUCTION

Due to the high level of built-up areas resulting from urbanization, infrastructure and the amount of green space surrounding it significantly determine the appearance of urban areas. Considering the increasingly modern appearance of settlements and today's accelerated pace of life, more and more attention is being paid to the surrounding environment. Therefore, the creation of a pleasant environment is one of the important factors in the development of urban areas.

When planning and implementing urban development projects, it is of great importance to monitor and pay attention to environmental protection, longevity, and the sustainability of solutions. Whether we are talking about parks, tree avenues, or solitary trees, the presence of trees and forests in urban environments has a much greater value than appearance alone. Regardless of whether it is a large forest complex or only a few trees, the benefits they provide are numerous and are felt at both the local and global levels.

The advantages and benefits of urban trees range from intangible psychological and aesthetic benefits to improvements in the urban climate and reductions in air pollution.

2. STUDY AREA

The study area selected for this research is Adžija Square, popularly known as “Drveni plac” (“Wood Market”), in Karlovac. It is one of the three historic parks within the Karlovac Star (Karlovačka zvijezda).

The park is located in the area between Haulikova and Kukuljevićeva Streets. The site acquired its unusual name because of the firewood trade that took place there. A residential block was formerly located at this site, but it was destroyed in a fire in 1878. At the initiative of Josip Adžija, the then-president of the Society for the Beautification of the City of Karlovac, the area was subsequently arranged as a park with benches and a lawn, decorated with rows of horse chestnut trees.

Today, the park is, in a sense, forgotten and remains outside the scope of everyday public attention.

3. METHODS

The VTA (Visual Tree Assessment) method is used to assess structural damage and tree stability. Using this method, a detailed visual inspection of the tree, crown, and branches is carried out, including the identification of symptoms, the detection of fruiting bodies of wood-decay fungi, and other symptoms indicating the presence of plant diseases and pests, as well as other abiotic factors. The purpose is to identify changes that indicate structural damage and may lead to reduced tree stability.

In addition to mechanical aspects, biological components are also examined, allowing the vitality of the tree to be assessed. If a tree has no significant damage and has sufficient vitality to recover after a branch or stem failure, it is not considered hazardous.

If it is not possible to determine through visual assessment whether a tree is potentially hazardous and whether remediation is required for the safety of pedestrians and users of the area where the tree is located, additional investigations using arboricultural instruments are carried out. Their purpose is to assist in the assessment when the visual examination does not provide sufficient certainty about the condition of the tree. These instruments can help confirm or refute the findings of the visual assessment.

The VTA method can be used to identify hazardous trees and prescribe the necessary arboricultural interventions near roads [10] and in urban forests [11].

Some of the additional methods used to assess tree condition include tapping the bark with a hammer to detect cavities located near the surface by listening for a hollow sound. Drilling is one of the most common methods. A drill is used to penetrate approximately 2–5 cm into the trunk (with a drill bit measuring 3.2 mm in diameter and 22.9 cm in length). After extraction, the condition of the tree is assessed based on the colour, texture, and odour of the extracted sample, as well as the resistance encountered by the tree during drilling [12].

For the purposes of this study, we used the direct micro-drilling method with an IML-RESI PD 400 resistograph. The obtained data were processed using the “IML Software PD Series”.

4. RESEARCH RESULTS

The study area, locally known as “Drveni plac”, is located next to the Nursing Home for Older Persons in Karlovac. Therefore, assessing the condition of the trees was of exceptional importance, both because of pedestrians passing by the park and because of the residents of the nursing home, who use the park for daily walks.

There are 21 trees in the park, of which 17 were examined in this study. Not all trees were examined because some were newly planted and therefore did not require testing. There is also a veteran tree without a crown; in the event of its failure, it would not pose a significant risk to pedestrians or park users.



Fig. 1: Adžija Square - Karlovac

4. DISCUSSION

The instruments used to examine the condition of the trees in Drveni park, namely the resistograph and Pressler increment borer, indicated potential hazards to park users and pedestrians.

As previously mentioned, the park is located in the immediate vicinity of a nursing home for older persons, making it particularly important to assess the stability of the trees. Based on the measurements performed on each individual tree, we obtained results that were subsequently analysed using graphical representations generated by the resistograph.

We observed that the majority of the trees appeared visually healthy and well-maintained; however, their internal structural condition was significantly compromised. Consequently, most of the trees were identified as requiring remediation.

Trees numbered 1, 2, and 3 (*Aesculus hippocastanum* – horse chestnut) are located in the immediate vicinity of roads and therefore represent a significant risk of tree failure onto the roadway.

The analysis of trees numbered 4, 5, 6, 7, and 8 (*Aesculus hippocastanum* – horse chestnut) showed that, based on visual assessment, the trees appeared to be in good condition. However, resistograph measurements indicated the presence of fungal decay within the trees.

Tree number 9 (*Aesculus hippocastanum* – horse chestnut) is a veteran tree without a crown. It has been retained in the park as a habitat supporting biodiversity, including cockroaches, insects, and other organisms.

Trees numbered 10, 20, and 21 (*Aesculus hippocastanum* – horse chestnut) were not measured because they are newly planted and therefore did not require an assessment of their current condition.

The analysis of trees numbered 11, 12, 13, and 14 (*Aesculus hippocastanum* – horse chestnut) revealed the presence of fungal decay within the trees. After a certain depth, all of these trees were found to contain internal cavities.

Trees numbered 17 and 18 (*Aesculus hippocastanum* – horse chestnut) have become strongly inclined to one side, in the direction of available light. Due to their height, they pose a significant risk of potential failure.

A sample was taken from tree number 19 using a Pressler increment borer and compared with the results obtained from the resistograph graph. The comparison showed minor deviations between the measurements.

During the visual inspection of the park, it was also concluded that most of the trees have a potential risk of branch failure at branch unions and forks.

5. CONCLUSION

Urban forests are of exceptional importance, and consequently there is an increasing need for their protection, particularly today, when they are threatened by various forms of pollution and construction activities in their vicinity.

It is also necessary to educate people who believe that passive protection alone is sufficient. Urban forests must be professionally and responsibly managed in order to maintain these forests and ecosystems in a healthy condition while simultaneously contributing to the reduction of carbon dioxide (CO_2) emissions.

As part of this study, testing was carried out on all potentially hazardous trees in the park under investigation. The instruments used were a resisgraph and a Pressler increment borer, enabling the tree assessments to be performed as thoroughly and accurately as possible.

The resistograph is one of the advanced instruments used in modern urban forestry and arboriculture for assessing trees in urban areas. Although the tree assessments indicated that there may be potential risks of tree or tree-part failure, the current level of risk is still considered low, since more precise investigations are required before any type of remediation can be recommended.

The safety of pedestrians and park users is of primary importance. Therefore, timely and appropriate decisions need to be made. Similar decisions have been implemented over previous decades, and it can be assumed that, if any significant risk is identified, appropriate measures will be taken in a timely manner.

Ultimately, every tree, or any part of a tree, can fail and cause injury to people or property damage. Therefore, trees should be assessed in order to determine the level of risk they represent.

There are no completely safe trees, and it is not possible to guarantee that any individual tree is entirely safe or that it will never fail or lose a branch or other part. For this reason, trees should be continuously monitored and inspected using different assessment methods. Through continuous education and consultation with experts, urban trees can be managed properly and safely.

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Professional paper

ENSURING OCCUPATIONAL HEALTH AND SAFETY IN CHEMICAL LABORATORIES

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Abstract: *Occupational health and safety (OHS) in chemical laboratories is essential for protecting workers from the diverse hazards associated with chemical substances. Laboratory environments often involve toxic, flammable, corrosive, and reactive chemicals, which can cause acute injuries or long-term health effects if proper safety measures are not followed. The first step in OHS practices is hazard identification and risk assessment, supported by clear labeling and access to Safety Data Sheets (SDS), which provide information on chemical properties, hazards, and safe handling procedures. Risk mitigation should follow the hierarchy of controls, beginning with elimination of hazards and substitution with less hazardous chemicals or procedures, followed by engineering controls such as fume hoods and ventilation systems, administrative controls like standard operating procedures and training programs, and finally personal protective equipment, including gloves, lab coats, and eye protection. Additionally, safe handling and proper storage further reduce the likelihood of accidents. Implementing these measures ensures a safer and more efficient laboratory environment.*

Keywords: *laboratory, chemicals, safety, hazards*

1. INTRODUCTION

Chemical laboratories are essential environments that support scientific research, education, and technological development across many disciplines, including chemistry, biology, medicine, and engineering. In the laboratory, a wide variety of experimental procedures are carried out using substances that may present significant health and safety risks if not properly managed. International occupational safety frameworks, including guidance from the World Health Organization (WHO) [1] and the International Labour Organization (ILO) [2], emphasize that workplaces handling hazardous materials must implement strict control measures to prevent occupational injury and disease.

In laboratory environments, exposure to chemical hazards such as toxic, flammable, corrosive, and reactive substances can result in both immediate and long-term health effects. These may range from acute injuries like burns, poisoning, and respiratory irritation to chronic conditions caused by prolonged or repeated exposure. Because of these risks, maintaining safe working conditions and preventing occupational exposure are fundamental aspects of laboratory practice.

This paper reviews the key principles of occupational health and safety in chemical laboratories, focusing on hazard identification, risk assessment, and the implementation of control measures. These processes allow laboratory workers to recognize potential dangers and implement appropriate preventive measures. Key tools supporting these efforts include proper chemical labeling systems [3] and access to Safety Data Sheets (SDS) [4], which provide detailed information on chemical properties, hazards, and recommended handling procedures. To minimize risks, laboratories must adopt a multi-layered approach to safety. This includes elimination of hazards and substitution with less hazardous chemicals or procedures, followed by engineering controls [5] such as fume hoods and ventilation systems, administrative controls [7] including training programs and standard operating procedures, and finally the use of personal protective equipment [6] such as lab coats and eye protection as the last level of protection.This paper outlines these elements and highlights the importance of a proactive and integrated approach to laboratory safety, ultimately contributing to a safer and more efficient working environment.

2. DISCUSSION

2.1. Hazards in Chemical Laboratories

Laboratories present a wide range of hazards that can pose significant risks to personnel if they are not properly recognized, assessed, and controlled. These hazards may originate from the chemicals used, laboratory equipment, or experimental procedures performed during routine work. Hazardous chemicals are generally classified based on their physical dangers, such as flammability, explosivity, and corrosivity, or their ability to cause harmful health effects through acute or chronic exposure [8].Flammable chemicals are among the most common laboratory hazards. Organic solvents such as ethanol, methanol, acetone, and hexane have low flash points and can easily ignite in the presence of ignition sources such as open flames, sparks, or hot surfaces. Their vapors may travel and ignite remotely, creating flashback fire hazards. Explosive risks may also arise from unstable substances formed during storage. For example, peroxide-forming chemicals such as diethyl ether and tetrahydrofuran can develop shock-sensitive peroxides when exposed to air and light over time [6,7,8].Corrosive chemicals, including strong acids and bases, can cause severe burns and damage to the skin, eyes, and respiratory system. Certain substances, such as hydrofluoric acid, present particularly serious dangers because they can penetrate deep into tissue and cause systemic toxicity. Cryogenic liquids, including liquid nitrogen and liquid helium, also pose hazards such as frostbite, oxygen displacement, and pressure buildup in sealed containers .

In addition to physical hazards, many chemicals present important health risks. Acute exposure may result in irritation, dizziness, nausea, poisoning, or respiratory distress, while chronic exposure can contribute to liver and kidney damage, neurological disorders, or cancer. Highly toxic substances such as sodium cyanide or hydrogen sulfide may be fatal even at low concentrations. Some chemicals are classified as carcinogens, mutagens, reproductive toxins, or teratogens because they can cause cancer, genetic mutations, fertility problems, or developmental abnormalities. Chemical sensitizers such as isocyanates, formaldehyde, and nickel compounds may also trigger allergic skin or respiratory reactions after repeated exposure. Due to the wide variety of hazards present in laboratory environments, proper hazard identification and effective safety measures are essential for protecting laboratory personnel and maintaining safe working conditions [6,7,8].

2.2. Chemical identification, labeling and storage

In the European and Croatian regulatory framework, employers who work with hazardous chemicals are required to assess and reduce risks, ensure appropriate labeling and access to Safety Data Sheets (SDS), and provide workers with information, training, and appropriate preventive measures. These requirements are supported by the CLP Regulation, Directive 98/24/EC [9, 10], and the Croatian Regulation on the Protection of Workers from Risks due to Exposure to Hazardous Chemicals at Work [11]. OSHA requirements represent the U.S. regulatory framework and may also be used as an additional reference for good laboratory safety practice.

In workplace, chemical identification is a critical step in risk management. Every chemical substance or mixture must be clearly identified by its name and, where applicable, by additional identifiers such as CAS (Chemical Abstracts Service) numbers [12], since substances with similar trade names may have very different hazards and toxicological properties.

Information about hazards and safe handling procedures is provided through the SDS. SDSs contain standardized information on hazard identification, first aid, handling and storage, exposure controls, toxicological properties, and emergency measures [4, 13]. Chemical containers are properly labeled with essential information such as product identifiers, hazard statements, precautionary statements, pictograms, and manufacturer details to ensure safe handling and hazard recognition [13]. In Croatia, these requirements are complemented by national regulations on the protection of workers from exposure to hazardous chemicals, including requirements for access to SDS information and appropriate labeling of containers [11]. Chemicals should be stored separately, in designated cabinets, according to their hazard class and chemical compatibility, with incompatible groups such as acids and bases, oxidizers and organic or flammable substances, water-reactive substances, and cyanides and acids kept apart to prevent dangerous reactions. Temperature-sensitive or flammable substances require appropriate refrigeration units, while chemicals should generally be kept away from heat sources, direct sunlight, and unstable storage locations to reduce the risk of spills, degradation, or accidental release [4]. When chemicals are transferred into secondary containers, those containers must also be properly labeled to maintain traceability and ensure access to the correct SDS in emergencies.

Hazard warning signs and pictograms are standardized visual tools used to communicate chemical hazards quickly and clearly (Figure 1). Based on the Globally Harmonized System (GHS), these symbols indicate hazards such as toxicity, flammability, corrosivity, and other health risks [3,8]. The overview of chemical hazards and associated safety protocols is presented in Table 1.

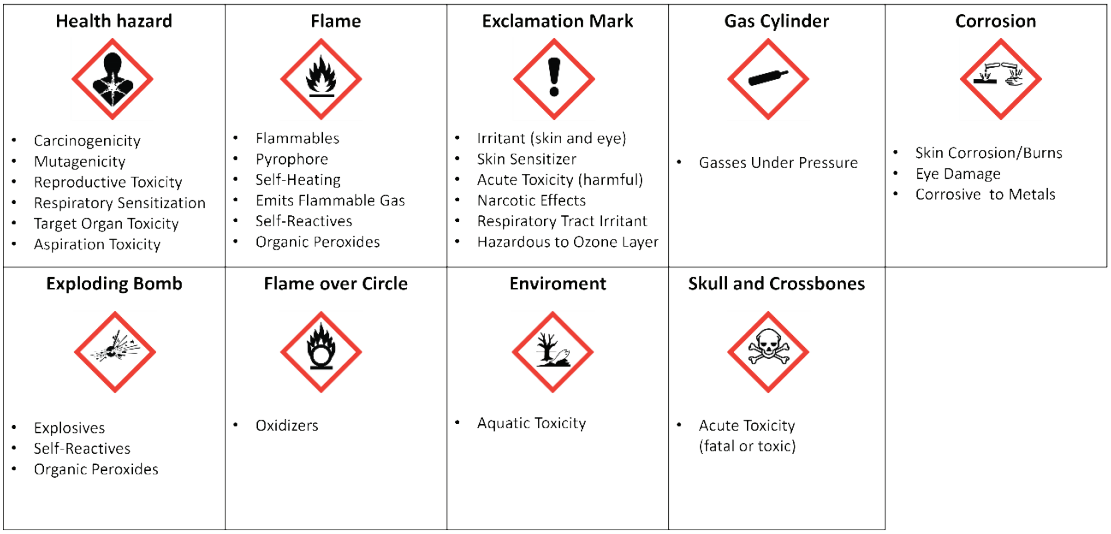


Figure 1: Pictograms and Hazards [3].

Table 1: Overview of chemical hazards and associated safety protocols, compiled by the authors based on the multiple sources and Safety Data Sheets (SDSs) 3,.

Hazard	Description and Example	Storage and Handling	First Aid
Flammable	Substances that easily catch fire. Example: petrol, ethanol, propane	Store in ventilated areas away from heat, sparks, and open flames, use approved containers and ventilation	Move person away from fire, cool burns with water, seek medical attention
Explosive	Substances that can rapidly release energy. Example: TNT, fireworks	Store in secure, temperature-controlled facilities away from impact and friction	Call emergency services, control bleeding, treat for shock
Corrosive	Chemicals that destroy living tissue or materials. Example: sulfuric acid, sodium hydroxide	Store in corrosion-resistant containers, avoid skin contact and handle in fume hood if needed	Rinse with water for at least 15 minutes, remove contaminated clothing, seek medical help
Cryogenic	Extremely cold substances. Example: liquid nitrogen	Store in insulated, vented pressure vessels, prevent pressure buildup, handle slowly	Warm affected area slowly, do not rub, seek medical attention
Toxic	Substances harmful or fatal if inhaled/ingested. Example: chlorine gas, pesticides, mercury	Store in sealed, labeled containers in ventilated, restricted areas, avoid inhalation/ingestion; use fume hoods; proper labeling	Move to fresh air immediately, seek urgent medical assistance

2.3. Engineering Controls for Occupational Safety in Chemical Laboratories

Engineering controls are a key component of laboratory safety and the primary means of controlling exposure to hazardous chemicals [5]. These controls are designed to reduce or eliminate hazards at the source rather than relying on worker behavior.

One of the most important engineering controls in chemical laboratories is the chemical fume hood. Fume hoods are designed to capture and remove hazardous vapors, gases, fumes, and aerosols generated during experimental procedures, thereby reducing inhalation exposure. Properly functioning ventilation systems are also essential for maintaining adequate air exchange and preventing the accumulation of toxic or flammable substances in laboratory air [5,7]. In addition, general ventilation systems play an essential role in maintaining overall indoor air quality by continuously supplying fresh air and diluting airborne contaminants throughout the laboratory environment.

Other important engineering controls include local exhaust ventilation systems, which remove contaminants directly at the point of generation, enclosed or closed chemical handling systems that minimize operator contact with hazardous substances, and safety cabinets specifically designed for the storage of flammable, corrosive, or toxic chemicals [5, 7]. Glove boxes [7] are used for handling highly toxic, reactive, or air-sensitive materials by fully isolating the substance from the laboratory environment while clean rooms [5] are used in specialized laboratories to minimize contamination and maintain strict environmental conditions.

Emergency showers, eyewash stations, and fire extinguishers are essential laboratory safety equipment used for immediate response to accidents. Showers and eyewash stations provide rapid decontamination after chemical exposure by by flushing affected skin or eyes with water; the duration and procedure should follow the SDS and specific requirements of the chemical involved. For hydrofluoric acid exposure, a specific emergency protocol and immediate medical treatment are required.. Fire extinguishers are used to control small, incipient fires and are classified based on the type of fire: Class A (ordinary combustibles), B (flammable liquids), C (flammable gases), D (combustible metals), and F (cooking oils and fats) 14. The effectiveness of engineering controls depends on proper design, regular maintenance, inspection, and user training. Fume hoods and ventilation systems should be routinely tested to ensure adequate airflow and compliance with occupational safety standards.

2.4. Administrative Controls for Occupational Safety in Chemical Laboratories

Administrative controls are policies, procedures, and work practices designed to reduce the risk of exposure to hazardous chemicals and unsafe conditions in chemical laboratories [4]. Unlike engineering controls, which physically isolate hazards, administrative controls focus on managing human behavior and organizational processes to prevent accidents and injuries.

One of the most important administrative controls in chemical laboratories is the development and implementation of standard operating procedures (SOPs) together with effective hazard communication programs. SOPs provide detailed instructions for handling chemicals, operating laboratory equipment, disposing of hazardous waste, and responding to emergencies, helping workers perform tasks safely and consistently while reducing the likelihood of errors and accidents [7,15]. At the same time, laboratories should maintain accurate labeling of all chemical containers and provide access to Safety Data Sheets (SDS) to ensure that workers understand the risks associated with the chemicals they use and the precautions required for safe handling.

Training and education are also critical administrative controls. Laboratory workers must receive proper instruction on chemical hazards, safe handling techniques, emergency procedures, and the correct use of personal protective equipment (PPE). Regular refresher training ensures that employees remain aware of safety practices and updated regulations. Safety training also promotes a culture of responsibility and awareness within the laboratory environment 5.

Work scheduling and limiting the time workers spend handling highly toxic substances can reduce exposure risks. Supervisors should monitor laboratory activities to ensure compliance with safety procedures and intervene when unsafe practices are observed.

Emergency preparedness is another aspect of administrative control. Laboratories should establish emergency response plans for chemical spills, fires, explosions, and exposure incidents. Regular emergency drills help employees practice evacuation procedures and improve their response during real emergencies. Contact information for emergency personnel and the location of emergency equipment should always be clearly displayed.

2.5. Personal protective equipment (PPE) for Occupational Safety in Chemical Laboratories

Personal protective equipment (PPE) refers to specialized clothing and equipment that minimize worker exposure to chemical, physical, and biological hazards. PPE includes a wide range of protective items such as laboratory coats, gloves, safety goggles, face shields, respirators, hearing protection, and protective footwear. In the event of an accident, PPE serves as an essential protective barrier against injury and hence laboratory personnel must maintain strong safety awareness and consistently wear the appropriate PPE during all experimental procedures .

The selection of appropriate PPE depends on the type and level of hazard present in the laboratory. Eye protection should be worn by personnel and visitors in areas where chemicals are stored or used when indicated by the risk assessment and the specific safety rules of the laboratory [5]. Safety glasses with side shields provide minimum protection, while chemical splash goggles are required for higher-risk procedures involving chemical splashes, pressurized systems, or hazardous reactions. [5,6] Face shields should be used in addition to goggles or safety glasses when there is a risk of severe splashing or flying particles. It is important to note that ordinary prescription glasses do not provide adequate laboratory protection, however, prescription safety glasses are available for use in laboratory environments .

Skin protection is another aspect of occupational safety in a chemical laboratory because laboratory personnel may come into direct contact with hazardous chemicals that can cause irritation, burns, allergic reactions, or other harmful health effects. To reduce these risks, appropriate personal protective equipment (PPE) such as lab coats or protective suits, shoes and gloves must be used. Since lab coats are commonly used in chemical laboratories, it is important to avoid wearing clothing that leaves large areas of skin exposed, such as shorts, sandals, or open-toed shoes [6]. Gloves should be carefully selected according to the chemicals handled, since no single glove material protects against all substances. Nitrile, neoprene, butyl, and Viton® gloves are commonly used for chemical resistance, but glove selection should be based on the manufacturer's chemical compatibility data, considering the chemical concentration, glove thickness, degradation, permeation, and breakthrough time. Latex gloves may provide inadequate protection against some solvents and may also pose a risk of allergic reactions [5,6]. Good laboratory practices, including frequent glove replacement, proper hand washing, and avoiding contact with common surfaces while wearing contaminated gloves, are also important for maintaining safety. Cryogenic gloves should be used when handling cryogenic liquids such as liquid nitrogen to avoid frostbites.

The use of respirators in a chemical laboratory should only be considered when other methods of controlling inhalation hazards are not sufficient. It is important that workers undergo a medical evaluation before initial respirator use and whenever health or work conditions indicate the need for reassessment, along with a fit test to verify that a tight-fitting respirator forms a proper seal on the face. It is also essential to use the correct filter cartridges, since respirators are designed to protect only against specific chemicals and vapors .

3. CONCLUSION

Chemical laboratories are essential environments for scientific progress, but they also present significant occupational risks due to the frequent use of hazardous substances and complex experimental procedures. As discussed in this paper, these hazards range from immediate physical

dangers such as fires, explosions, and chemical burns to long-term health effects including chronic toxicity, carcinogenicity, and reproductive damage.

The study highlights that effective laboratory safety is built on a structured and integrated occupational health and safety (OHS) system. Central to this system is the proper identification, classification, and communication of chemical hazards through labeling and Safety Data Sheets (SDS), which enable workers to understand the risks associated with each substance they handle. In addition, risk management in chemical laboratories depends on the effective application of the hierarchy of controls. Engineering controls, such as fume hoods, ventilation systems, glove boxes, and safety cabinets, provide the first and most effective barrier by minimizing exposure at the source. Administrative controls, including standard operating procedures (SOPs), training programs, hazard communication systems, and emergency preparedness plans, ensure that safe practices are systematically followed and reinforced. Personal protective equipment (PPE), although considered the least effective control on its own, is still crucial as the last line of defense when other measures cannot completely remove exposure risks.

Ultimately, a proactive and well-implemented occupational safety framework not only reduces accidents and health risks but also enhances efficiency, supports high-quality research outcomes, and fosters a responsible scientific working environment.

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Professional paper

A SECOND LOOK AT OCCUPATIONAL SAFETY MANAGEMENT IN ENTERPRISES: A PTM-I HEAT-MAP METHOD FOR STAKEHOLDER-BASED MONITORING

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Abstract: *This professional paper introduces PTM-i, a lightweight multi-criteria monitoring method for occupational safety and health (OSH) management in enterprises. The objective is to determine whether a repeatable stakeholder survey can reveal weak OSH criteria and differences among role-based assessments before formal management review. Five stakeholder groups rate nine criteria on a five-point ordinal scale; valid ratings are aggregated into group means, an equally weighted criterion mean, an inter-group sample standard deviation, a normalized PTM-i index and a heat map. A simulated demonstrative scenario—used to illustrate implementation rather than to provide empirical validation—produced the lowest criterion means for corrective-action closure (2.58), incident and near-miss reporting (2.70), and contractor control (2.72). These outputs show how management can select verification and follow-up priorities. PTM-i is platform-independent; R/Shiny is only one demonstrator. Unlike TOPSIS or VIKOR, PTM-i does not rank strategic alternatives against weighted decision criteria; it provides a transparent screening layer that complements risk assessment, statutory audits and ISO 45001 processes. Real-enterprise validation, sensitivity analysis of thresholds and weights, and comparison with incident indicators and established MCDM rankings remain necessary.*

Keywords: *occupational safety and health; PTM-i; heat map; stakeholder survey; multi-criteria decision-making*

1. INTRODUCTION

Occupational safety and health (OSH) systems are usually managed through risk assessment, workplace inspections, training records, statutory documentation and corrective actions. These mechanisms are necessary, but they can create a delayed or document-heavy view of daily safety performance. The practical state of the system is distributed among several stakeholder groups: the OSH manager, production managers, maintenance, worker safety representatives and external authorized providers. If their assessments are not collected in a structured and repeatable way, weak signals may remain hidden until they appear as incidents, delays or nonconformities.

Existing controls provide essential evidence, yet they do not by themselves offer a low-cost and repeatable comparison of how different roles perceive the same OSH criteria. The resulting practical gap lies between document-based compliance information and timely stakeholder signals. A “second look” is therefore not another audit layer, but a compact monitoring layer between informal conversation and formal management review. PTM-i addresses this gap by collecting role-specific scores, calculating group means and inter-group dispersion, displaying a heat map, and repeating the survey after corrective measures. This scope follows the participation and continual-improvement orientation of modern OSH management systems [1] and the European worker safety framework [2].

The paper addresses three practical questions: can a role-based survey identify weak OSH criteria; can inter-group dispersion reveal where stakeholder assessments diverge; and can a heat map support corrective-action priorities and follow-up? Its contributions are (i) a transparent data and aggregation model, (ii) a platform-independent workflow from survey input to verification, and (iii) an explicit boundary between rapid PTM-i screening and formal methods such as TOPSIS and VIKOR. Because the scenario uses simulated data, this professional paper demonstrates feasibility and interpretation but does not claim predictive accuracy or real-enterprise validation.

2. METHODOLOGICAL BASIS

2.1 Survey structure

The proposed model uses a short ordinal questionnaire. Before each cycle, the organization defines the organizational unit, reference period, criteria, common rating anchors and administration mode. Respondents rate independently on a five-point scale, where 1 indicates a critical condition and 5 a fully satisfactory condition. Each record contains the cycle date, organizational unit, respondent code, stakeholder group, criterion, rating and an optional evidence comment. Validation accepts only documented stakeholder and criterion codes and integer ratings from 1 to 5; missing ratings are not imputed, and only one rating per respondent–criterion–cycle combination is retained according to a documented rule. Cell counts should accompany aggregated results, while identifiable comments remain access-controlled. The stakeholder groups and their typical evidence are shown in Table 1.

Table 1: Proposed stakeholder and evidence structure

Stakeholder group	Main evidence contributed to the survey
OSH manager	Risk assessment, corrective actions, training, audits and statutory records.
Production managers	Daily work organization, safe behaviour, productivity pressure and communication.
Maintenance manager	Machine guarding, preventive maintenance, lockout practice and emergency readiness.
Worker safety representatives	Unsafe conditions, PPE use, reporting culture and worker participation.
External OSH providers	Authorized examinations, training, specialist observations and contractor interface.

2.2 Aggregation, dispersion and PTM-i index

For criterion j and stakeholder group k, the mean rating is calculated according to Eq. (1), where s_ijk is the rating given by respondent i and n_jk is the number of valid ratings. The overall criterion mean $\bar{x}_j$ is the arithmetic mean of K_j valid group means $\bar{x}_{jk}$, so every stakeholder group contributes equally rather than in proportion to its respondent count. Accordingly, n_jk and K_j should be reported and unequal group sizes examined in sensitivity analysis.

$$\bar{x}_{jk} = \frac{1}{n_{jk}} \sum^{n_{jk}} s_{ijk} \quad (1)$$

Inter-group sample standard deviation is used as a dispersion indicator and is calculated from the valid group means according to Eq. (2), where K_j is the number of groups contributing to criterion j. A low value indicates similar group assessments, whereas a high value indicates divergence that should be discussed before a managerial conclusion is accepted. No SD is reported when K_j is less than two, and SD should not be interpreted as measurement reliability or statistical confidence.

$$SD_j = \sqrt{\frac{\sum_{k=1}^{K_j} (\bar{x}_{jk} - \bar{x}_j)^2}{K_j - 1}} \quad (2)$$

For monitoring and comparison, Eq. (3) linearly rescales the criterion mean from 1–5 to the normalized PTM-i interval 0–1. The demonstrative interpretation bands were specified as follows: x̄_j < 2.70, critical priority; 2.70 ≤ x̄_j < 3.00, improvement needed; 3.00 ≤ x̄_j < 4.00, monitor; and x̄_j ≥ 4.00, satisfactory. These are configurable screening rules, not legal compliance limits. Equal weighting supports transparent screening, while formal weighting, TOPSIS, VIKOR or another MCDM procedure is appropriate when management must rank alternatives or test the robustness of priorities [3–6].

$$I_j^{\mathrm{PTM}} = \frac{\bar{x}_j - 1}{4} \quad (3)$$

3. PTM-i IMPLEMENTATION AND DEMONSTRATOR

PTM-i is intentionally platform-independent. The calculation can be implemented in R, Python, JavaScript, spreadsheet software or any other environment that supports basic aggregation and visualization. In this paper, R and Shiny are used only to build a demonstrator because they provide statistical calculation, data transformation and a web interface that non-programmers can use [7, 8].

The demonstrator contains a survey form, validation rules, storage in CSV or SQL format, a heat map by criterion and stakeholder group, a trend plot of the PTM-i index, and an exportable data table for audit trail. Visualization can be built with the same grammar of graphics used in ggplot2 [9], but the method itself is not dependent on ggplot2 or Shiny. The complete monitoring flow from survey input to follow-up verification is presented in Figure 1.

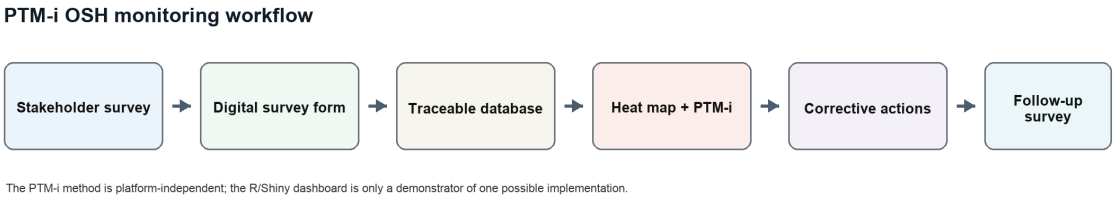


Figure 1: PTM-i workflow from stakeholder survey to corrective action.

The workflow should be governed carefully. The survey must be short enough to be completed repeatedly, comments should focus on evidence rather than blame, and personal data should be minimized. Role-based aggregation is usually sufficient for management review, while raw comments should be visible only to authorized persons. The dashboard supports decision preparation; it does not replace risk assessment, incident investigation, inspection records or statutory expert judgement.

4. DEMONSTRATIVE SCENARIO

4.1 Data and heat-map interpretation

A simulated matrix of group-level means was prepared for a hypothetical medium-sized production enterprise. Five stakeholder groups and nine OSH criteria produce 45 heat-map cells; each cell is an illustrative group mean rather than a raw respondent rating. Table 2 applies equal group weighting and the sample SD in Eq. (2) to the five cell values for each criterion. No personal or enterprise data and no inferential statistics are used, so the scenario cannot establish prevalence, causation or effectiveness. It serves only to test the transparency of the calculation, visualization and management workflow. Numerical cell labels preserve readability when the heat map is printed without colour.

Demonstrative OSH heat map by criterion and stakeholder group

Criterion	OSH manager	Production managers	Maintenance manager	Worker safety reps.	External OSH providers
Risk assessment update	3.4	3.1	3.2	2.9	3.6
Training and competence	3.5	3.2	3.0	2.8	3.4
PPE use and availability	3.7	3.1	3.3	2.9	3.5
Machine maintenance safety	3.1	2.8	2.4	2.6	3.2
Incident and near-miss reporting	2.9	2.5	2.7	2.4	3.0
Contractor control	3.0	2.7	2.6	2.5	2.8
Corrective action closure	2.8	2.4	2.5	2.3	2.9
Communication and participation	3.2	2.7	2.9	2.5	3.1
Emergency readiness	3.6	3.3	3.2	3.0	3.5

Scale: 1 = critical, 5 = satisfactory. Hatching marks values below 2.7.

critical warning satisfactory

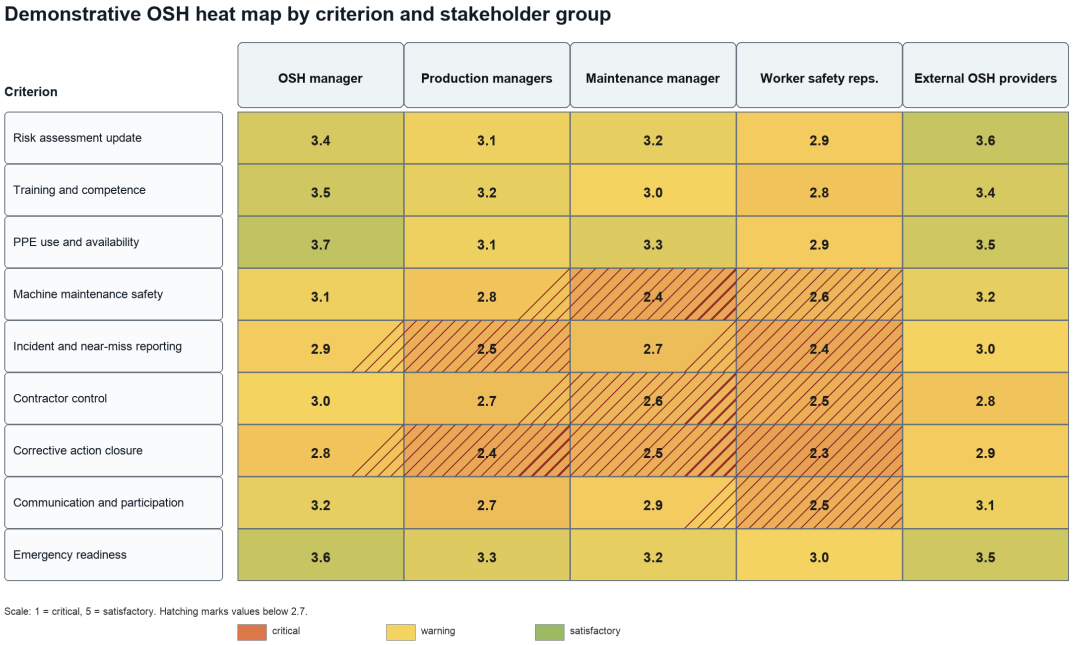


Figure 2: Demonstrative heat map of average OSH ratings by criterion and stakeholder group.

Table 2: Demonstrative criterion means and consensus indicators

Criterion	Mean	SD	Interpretation
Risk assessment update	3.24	0.27	Monitor
Training and competence	3.18	0.29	Monitor
PPE use and availability	3.30	0.32	Monitor
Machine maintenance safety	2.82	0.33	Improvement needed
Incident and near-miss reporting	2.70	0.25	Improvement needed
Contractor control	2.72	0.19	Improvement needed
Corrective action closure	2.58	0.26	Critical priority
Communication and participation	2.88	0.29	Improvement needed
Emergency readiness	3.32	0.24	Monitor

4.2 Management use

The weakest criteria in the demonstrative scenario are corrective action closure, incident and near-miss reporting, contractor control and machine maintenance safety. Worker safety representatives also rate several criteria lower than management and external providers. This difference is not an error; it is an important management signal. It indicates where the formal system may look acceptable while workers experience unresolved issues in daily work.

A practical response would be to assign owners and due dates for open actions, simplify near-miss reporting, introduce pre-start checks for contractors, and hold a short weekly coordination meeting between production, maintenance and OSH. The next survey cycle can then test whether the heat-map cells and the PTM-i index improve. In this way the model supports the plan-do-check-act logic without creating a heavy administrative instrument.

5. DISCUSSION

The main advantage of the proposed framework is transparency. Management can see not only which criterion is weak, but also which stakeholder group perceives it as weak and whether there is disagreement. This is useful for OSH because many problems are socio-technical: the same machine, procedure or contractor can be evaluated differently by production, maintenance and worker representatives.

The model also has clear limits. Ratings may be affected by response bias, fear, fatigue, common-method effects, question wording, small or unequal group sizes, missing data and sensitivity to selected thresholds. Equal group weighting prevents large groups from dominating but gives a small group the same influence as a large group; the group counts must therefore remain visible. Inter-group SD indicates divergence, not reliability, and a high score cannot prove legal compliance while a low score cannot identify a root cause by itself. The heat map should trigger verification through workplace inspection, document review, incident analysis, maintenance records, exposure measurements or another suitable method. Real-world validation should predefine criteria and thresholds, evaluate response stability across cycles, and compare PTM-i priorities with audit findings and lagging and leading OSH indicators.

PTM-i, TOPSIS and VIKOR address different decision tasks. PTM-i maps criterion weakness and stakeholder divergence without defining ideal alternatives or a compromise parameter. TOPSIS ranks alternatives by their distance from ideal and anti-ideal solutions [5], whereas VIKOR balances group utility and individual regret to identify a compromise ranking [6]. PTM-i can therefore provide diagnostic evidence before a formal MCDM analysis; TOPSIS or VIKOR is preferable when explicit alternatives, weights and trade-offs must be ranked. A rigorous comparison should apply all methods to the same real cases and examine ranking agreement and sensitivity to weights, thresholds and missing data.

6. CONCLUSION

This paper proposed PTM-i as a transparent and repeatable screening method for a stakeholder-based “second look” at OSH management. The method combines a five-point scale, role-based aggregation, inter-group dispersion, a normalized index and heat-map visualization. The simulated R/Shiny scenario demonstrates one implementation and yields illustrative priorities, but it does not establish measurement validity, causal effects or enterprise performance. The practical contribution is a platform-independent workflow that makes weak signals and stakeholder differences visible while preserving the authority of statutory OSH processes.

Future work should validate the model with real enterprise data, predefined minimum group sizes and repeatable administration; test anonymous and authenticated modes; and assess sensitivity to weights and interpretation thresholds. The same cases should be analysed with PTM-i, TOPSIS and VIKOR, and their priorities compared with incident indicators, audit findings and corrective-action closure. Until such evidence is available, PTM-i should be used as a complementary management-review screen rather than as proof of compliance or a replacement for risk assessment and professional judgement.

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Professional paper

META PROGRAMS IN PRACTICE: ENHANCING EMPLOYEE SAFETY BEHAVIOR

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Abstract: *Safety at work in industrial systems does not depend solely on technical measures and procedures, but also on the way employees think, assess risk, and make decisions. Meta-programs are described as cognitive patterns that may influence information perception, communication, and behaviour in safety-critical situations. This paper presents the application of five meta-programs – internal and external reference, toward and away from (problems), options and procedures, sameness and difference, and sameness with exception – in the context of occupational safety. In addition, the paper links meta-program patterns with employees' mental health, particularly in relation to stress, cognitive load, and adaptation to change. The aim of the paper is to propose a practical communication framework for managers, trainers, and occupational safety professionals that may contribute to safety culture and employees' psychological well-being.*

Keywords: *meta-programs, occupational safety, safety culture, cognitive patterns, mental health.*

1. INTRODUCTION

Despite the continuous development of safety procedures, technical standards, supervisory mechanisms, and personal protective equipment, workplace accidents remain significantly linked to the human factor. Although organizations are increasingly focused on formalizing safety systems, practice shows that the mere existence of rules does not guarantee their consistent application in everyday work situations. The key challenge is not a lack of safety information, but differences in the way employees perceive, interpret, and apply this information in a specific work context. The same safety signal, instruction, or warning may be interpreted differently depending on individual cognitive patterns, prior experience, level of caution, and decision-making style. As a result, behavioural variability occurs under identical working conditions, which represents one of the key challenges in safety management.

Meta-programs are described in NLP literature as cognitive patterns or filters that may shape what individuals pay attention to, how they interpret information, and how they make decisions [1–4]. They are described as patterns associated with individual preferences in processing information, evaluating situations, and responding to the environment [1,3]. They may therefore influence whether employees rely more on their own judgement, procedures, potential consequences, or desired outcomes.

Understanding these patterns may enable more precise design of safety communication, more effective experiential learning, and a higher level of consistency in the application of safety procedures. Recognising differences in meta-programs may also contribute to the development of a safety culture in which messages are not delivered "in the same way to everyone," but are adapted to the ways in which different employees process information [1,3].

The application of meta-programs in occupational safety is considered in this paper as a conceptual approach. Although meta-programs have been described in NLP literature [1–4], their application in occupational safety and their possible relationships with employees' psychological well-being remain insufficiently investigated empirically. Therefore, the paper does not present primary empirical data or claim causal relationships. Instead, it considers possible implications of selected meta-program patterns for occupational safety, safety communication, and employees' psychological well-being.

2. ROLE OF META-PROGRAMS IN SAFE BEHAVIOUR AND EMPLOYEES' MENTAL HEALTH

Employees' safety behaviour may be understood as the result of the interaction between organisational requirements, the work environment, and individual characteristics. Although organisations strive to standardise work through procedures and safety rules, employees may not perceive or apply them in the same way. Differences in how situations are assessed, decisions are made, and safety-related actions are taken may be partly considered in relation to meta-program patterns [1–4].

In industrial systems, recognising these patterns may contribute to more effective design of safety messages, training, and preventive activities. The following sections present key meta-programs that may be relevant to how employees perceive risk, make decisions, and respond in safety-critical situations. Understanding them may enable greater awareness of individual differences in safety behaviour and more precise development of communication and preventive interventions in the workplace.

2.1. INTERNAL AND EXTERNAL REFERENCE

Individuals with a dominant internal reference base safety decisions primarily on their own judgement, experience, and personal sense of what is right in a given situation [1,3]. Their thinking style is characterised by reliance on internal evaluation criteria, which may support faster decision-making due to trust in their own judgement.

The potential advantage of this pattern lies in quick response and reliance on experience, especially in situations where clear instructions are not available or immediate action is required in the field. However, difficulties may arise when an employee's personal assessment differs from prescribed standards. In such cases, an internal conflict may emerge between personal experience and procedural requirements, where the employee may experience resistance or frustration if they perceive additional safety steps as unnecessary, even though they are mandatory.

In the long term, such a mismatch may lead to a reduced sense of professional recognition, lower motivation, and feelings of dissatisfaction, which may affect attention levels and consistency in work, potentially increasing the likelihood of errors.

Individuals with a dominant external reference assess safety through external sources such as procedures, rules, instructions, supervisors, or control systems [1,3]. Their sense of security in decision-making may largely depend on the clarity of guidelines and feedback from the environment.

This pattern is characterised by a need for confirmation of correct performance, where clearly defined procedures may contribute to a sense of safety and reduce uncertainty in work. However, challenges may arise when clear feedback regarding task performance or compliance with procedures is lacking.

In such situations, employees may experience increased cognitive load, uncertainty, and self-doubt, as they do not receive external confirmation of correct performance. In the long term, this may result in increased tension, hesitation in decision-making, and a reduced sense of confidence in their own work.

2.2. TOWARD AND AWAY FROM

Individuals with a dominant Toward pattern are motivated by achieving positive outcomes and focusing on what they want to accomplish [1,2,4]. Their attention is naturally directed toward benefits, progress, and desired states, and they may respond well to safety messages framed in terms of positive results and desired values. In a safety context, this pattern may contribute to increased motivation, as employees may more easily connect safe behaviour with concrete outcomes such as maintaining health, successfully completing tasks, or returning home without injury. Such an approach may enhance engagement and a sense of purpose in following safety rules. However, when relying exclusively on positive outcomes, there may be a risk of underestimating real hazards and dangers in the work environment.

This pattern may support a positive emotional orientation and a higher level of motivation, but in high-risk safety situations it may lead to a cognitive bias where potential dangers are pushed into the background, reducing caution and realistic risk assessment. If individuals rely solely on positive outcomes, sensitivity to risks may decrease, thereby potentially weakening timely recognition of hazardous situations.

Individuals with a dominant Away From (problem-oriented) pattern are primarily focused on avoiding risks, problems, and negative consequences [1,2,4]. Their attention is naturally directed toward what could go wrong, which may make them highly sensitive to hazards and deviations from safe working conditions. In a safety context, this pattern may contribute to a high level of caution and early identification of potential dangers. Such employees may clearly understand the consequences of non-compliance with rules, which may contribute to a reduction in risky behaviour.

However, when organisational communication is predominantly focused on hazards and errors, increased risk orientation may lead to elevated stress levels, tension, and a persistent sense of threat, which may negatively affect employees' mental health.

In the long term, continuous focus on identifying and resolving problems may result in increased cognitive load and emotional exhaustion, as the individual maintains a constant state of vigilance and focus on potential risks and deviations. This pattern may lead to mental fatigue, reduced attention levels, and impaired decision-making, which may in turn increase the likelihood of an incident.

2.3. OPTIONS AND PROCEDURES

Individuals with a dominant Procedures pattern prefer clearly defined steps, structured processes, and predefined ways of working [1,2,4]. They often associate safety with consistent adherence to rules and procedures, as these provide a sense of predictability and control. Such employees typically want to know what needs to be done, in what sequence, and according to which criteria.

In a safety context, this pattern may offer significant advantages, as it may support consistent application of safety rules, potentially reduce errors, and contribute to compliance with organisational standards. Employees oriented toward procedures may be reliable in carrying out checklists, inspections, and other activities that require precision and discipline.

However, in situations that deviate from routine working conditions, they may experience difficulties adapting quickly if no clear procedure exists for the new situation. Unclear requirements, frequent changes, or lack of structure may create a sense of uncertainty and increased cognitive load, as employees do not have a clear framework for action. Prolonged exposure to such conditions may lead to frustration, reduced confidence in decision-making, and increased stress, which may negatively affect situational judgement and overall work performance.

Individuals with a dominant Options pattern are oriented toward possibilities, alternatives, and different ways of achieving a goal [1,2,4]. Rather than focusing on a predefined path, they naturally consider what else could be done and whether more effective solutions exist.

In safety-related contexts, such employees may suggest process improvements, identify opportunities for optimisation, and adapt more easily to changing conditions. Their flexibility may be particularly valuable in complex and dynamic work environments where standard solutions are not always sufficient.

On the other hand, excessive focus on exploring alternatives may lead to deviations from prescribed procedures if the employee perceives a “better way.” At the same time, continuous questioning of possibilities and searching for new solutions may lead to increased cognitive load, particularly in environments that require fast decision-making and strict adherence to procedures. In such circumstances, employees may experience frustration due to limited space for creativity and initiative, which over time may affect motivation and engagement at work.

2.4. SAMENESS AND DIFFERENCE

Individuals with a dominant Sameness pattern primarily seek continuity, familiar patterns, and confirmation that the situation has not significantly changed [1–3]. Their attention is naturally directed toward what is known, stable, and consistent.

In a safety context, this means that such employees may often assess situations based on prior experience:

- “I have been doing this job for years.”
- “This equipment is the same as last time.”
- “There have been no problems so far.”

This way of thinking may contribute positively, as it supports stability, routine, and consistent application of proven procedures. However, risks may arise when changes occur gradually or are very subtle. Individuals with a Sameness orientation may be slower to notice them, as their attention is focused on similarities rather than deviations.

For example, during equipment inspection, an employee may conclude that everything is fine because the equipment appears almost identical to previous days, even though a minor defect has developed.

On the other hand, frequent or significant changes in the work environment may create a sense of uncertainty and increased cognitive load for these employees. Since stability may be an important source of psychological security for them, constant changes in procedures, workflows, or responsibilities may lead to frustration, stress, and a reduced sense of control over the work situation. In the long term, this may affect motivation, engagement, and decision-making quality, which may also have an impact on safety performance.

Individuals with a dominant Difference pattern naturally seek changes, deviations, and irregularities [1–3]. Their thinking style is based on comparing the current state with previous experience, with attention automatically drawn to what is different.

In a safety context, this may be a valuable characteristic, as such employees may be among the first to notice:

- changes in machine operation;
- unusual sounds;
- deviations from procedures;
- changes in colleagues' behaviour;
- new sources of risk.

Because of this, they may serve as an important source of early hazard detection and incident prevention.

However, a continuous focus on changes and deviations may also lead to increased cognitive load, as the individual constantly monitors what is unusual and requires attention. In dynamic work environments with frequent changes, such employees may develop a perception that "something is always changing" or that problems are never fully resolved. Over time, this may result in mental fatigue, frustration, and reduced concentration, which may affect risk assessment quality and potentially increase the likelihood of an incident.

2.5. PROACTIVE AND REACTIVE

Individuals with a dominant Proactive pattern naturally take initiative and are action-oriented [1,2]. Their attention is often directed toward what needs to be done in order to achieve a desired outcome or prevent a potential problem. Such employees may be less likely to wait to be warned about hazards or to receive detailed instructions; instead, they may independently take action when they perceive a need for intervention.

In a safety context, proactive employees may be among the first to report potential hazards, suggest improvements to safety procedures, or eliminate minor risks before they escalate into more serious issues. Because of this, they may play an important role in developing a preventive safety culture and early hazard recognition systems.

However, their tendency toward rapid action may sometimes lead to decisions made without full analysis of the situation or without consulting all relevant procedures. In highly regulated systems, it is important that their initiative remains aligned with safety rules and organisational requirements.

At the same time, individuals with a strong proactive pattern may take additional responsibility for solving problems and improving work processes. If their contributions are not recognised by the organisation, or if they continuously encounter barriers to implementing their ideas, this may lead to frustration, a reduced sense of effectiveness, and emotional exhaustion. Over time, this may result in decreased engagement, reduced attention, and lower involvement in safety-related activities.

Individuals with a dominant Reactive pattern tend to gather information, observe the situation, and assess circumstances before taking action [1,2]. They often seek to understand the broader context, obtain additional information, or receive confirmation before making a decision.

In a safety context, this approach may be beneficial as it supports more thoughtful decision-making and may reduce the likelihood of impulsive reactions. Reactive employees may carefully analyse situations before acting and may notice additional factors that proactive individuals, due to their speed of response, might overlook.

On the other hand, in situations that require immediate response or rapid hazard control, excessive waiting for additional information may delay necessary actions and increase exposure to risk.

Such employees may experience increased cognitive load in uncertain situations or when required to make quick decisions without sufficient information. Prolonged exposure to such demands may lead to stress, uncertainty in their own judgement, and reduced confidence in decision-making, which may affect performance in safety-critical situations.

2.6. SUMMARY OVERVIEW OF META-PROGRAMS IN THE CONTEXT OF CCUPATIONAL SAFETY

Different meta-programs may influence how employees perceive risk, make decisions, and respond in safety-critical situations [1–4]. To facilitate understanding of their potential practical impact in industrial environments, the following section presents a summary overview of key meta-programs, their behavioural patterns, and possible implications for occupational safety. The table presents possible implications of the selected meta-program patterns rather than established empirical outcomes.

Table 1: Overview of meta-programs in a safety context

Meta-program	Behaviour	Potential psychological risk
Internal reference	personal judgement	frustration when experience is not acknowledged
External reference	rules and procedures	stress due to lack of feedback

Meta-program	Behaviour	Potential psychological risk
Toward (goals)	focus on outcomes	underestimation of risk
Away from (problems)	focus on risk	emotional exhaustion and stress
Procedures	structured work approach	frustration due to lack of clear structure and rules
Options	flexibility and alternatives	frustration due to limited autonomy
Sameness	routine and continuity	stress due to frequent changes
Difference	detection of deviations	mental fatigue due to constant focus on changes

3. CONCLUSION

Meta-programs may represent an important theoretical and practical framework for considering how employees perceive safety, risk, and change in the work environment. Since they may be relevant to information selection, situation interpretation, and decision-making, their application may provide a deeper understanding of differences in employees' safety behaviour in both everyday and safety-critical situations.

In an organisational context, understanding meta-program patterns may contribute to more effective communication, adaptation of safety messages to different thinking styles, and greater employee involvement in safety management activities. This may contribute to a stronger organisation's safety culture, greater compliance with safety requirements, and potentially reduce the likelihood of human error.

At the same time, meta-programs may be relevant to how employees experience stress, change, uncertainty, and work demands. Certain patterns may represent an important resource for occupational safety, but in unfavourable organisational conditions they may also be associated with increased psychological strain, frustration, stress, or emotional exhaustion. Therefore, occupational safety and mental health may be viewed as interconnected elements of the organisational system.

By integrating an understanding of meta-programs into safety management processes, employee development, and organisational culture design, such an approach may contribute to improvements in safety behaviour, reduction of psychosocial risks, and support for employees' psychological well-being. Such an approach may represent a useful contribution to the development of sustainable, safe, and efficient industrial systems, while also providing a basis for further empirical investigation.

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Professional paper

NON-FORMAL EDUCATION AS PROOF OF PROFESSIONAL COMPETENCE OF WORKERS PERFORMING JOBS WITH SPECIAL WORKING CONDITIONS

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Abstract: *Non-formal education plays an important role in acquiring and demonstrating the professional competence of workers performing jobs with special working conditions. Unlike formal education, which provides officially recognized qualifications through the education system, non-formal education includes various forms of training and practical instruction aimed at developing job-specific skills. In occupational safety and health, such programs enable workers to gain the knowledge and practical competencies necessary for safe work in high-risk environments. According to the Ordinance on Jobs with Special Working Conditions, workers must meet prescribed health, psychophysical, and professional requirements. Non-formal training often represents a key method for acquiring practical competencies required for these jobs. Through adult education programs, workers develop the ability to recognize hazards and apply appropriate safety measures. This approach contributes to improving occupational safety and strengthening the culture of prevention in the workplace*

Keywords: *Non-formal education, Adult education, Occupational safety and health, Jobs with special working conditions, Professional competence*

1. INTRODUCTION

The changes that have characterized the labour market in recent decades have led to a growing need for the continuous acquisition of new knowledge and skills. Technological development, the digitalization of work processes, and increasingly complex employer requirements have resulted in a greater demand for flexible forms of education capable of responding rapidly to the needs of the economy [5,10]. At the same time, the field of occupational safety and health requires the continuous improvement of workers' competencies in order to reduce the number of workplace injuries and occupational diseases [6,7].

Jobs with special working conditions constitute a category of occupations in which increased hazards, harmful exposures, or physical demands necessitate additional requirements related to workers' health status, psychophysical characteristics, and professional competence [1,2]. Under such circumstances, the issue of demonstrating professional competence becomes particularly important.

Traditionally, professional competence has been associated with formal education and official certificates confirming acquired qualifications. However, the adoption of the Adult Education Act (Official Gazette No. 144/21) and the development of the Croatian Qualifications Framework have created opportunities for the recognition of competencies acquired through non-formal education and micro-qualification programmes [5,8].

The aim of this paper is to analyse the opportunities and challenges associated with recognising non-formal education as evidence of professional competence for workers performing jobs with special working conditions and to determine its contribution to the improvement of occupational safety and health.

2. NON-FORMAL EDUCATION AND LIFELONG LEARNING

The concept of lifelong learning is based on the idea that individuals continuously acquire new knowledge, skills, and competencies throughout their lives. The European Union recognizes lifelong learning as one of the key elements for the development of a competitive economy and a sustainable labour market [5,10].

Non-formal education refers to organized learning processes that take place outside the formal education system but have clearly defined objectives, content, and learning outcomes [3]. Unlike informal learning, which occurs spontaneously through everyday activities, non-formal education is planned and structured.

The advantages of non-formal education include:

- rapid adaptation to labour market needs,
- flexibility in programme content and duration,
- a strong emphasis on practical training,
- opportunities to acquire specific competencies,
- enhanced employability of workers [5,8,10]

In the field of occupational safety and health, this form of education enables the development of competencies that are directly related to specific workplaces and the risks to which workers are exposed [6].

3. PROFESSIONAL COMPETENCE AS THE FOUNDATION OF SAFE WORK

Occupational safety and health largely depend on the competence of workers. Numerous studies conducted by the European Agency for Safety and Health at Work (EU-OSHA) indicate that human error, lack of knowledge, and inadequate training are among the most common causes of workplace accidents [6].

Professional competence implies a combination of knowledge, skills, experience, and the ability to apply acquired competencies in practice.

In jobs with special working conditions, the importance of professional competence becomes even more evident, as the consequences of errors can be extremely serious [1,2]. Examples include operating machinery, working at heights, working in confined spaces, handling hazardous substances, working in the energy sector, and high-risk construction activities.

Quality education and training represent one of the most important preventive measures in occupational safety and health [6,7]. A worker who understands workplace hazards, is familiar with safety procedures, and correctly uses work equipment is significantly less likely to be involved in incidents that result in injuries or material damage.

4. LEGAL FRAMEWORK OF THE REPUBLIC OF CROATIA

The legal framework governing jobs with special working conditions in the Republic of Croatia consists of:

- the Occupational Safety Act (Official (Gazette Nos. 71/14, 118/14, 154/14, 94/18 and 96/18),
- the Ordinance on Jobs with Special Working Conditions (Official Gazette No. 5/84),
- the Adult Education Act (Official Gazette No. 144/21),
- the Croatian Qualifications Framework Act (Official Gazette No. 22/2013),
- secondary legislation related to adult education and micro-qualifications.

The Ordinance on Jobs with Special Working Conditions stipulates that workers must satisfy specific health, psychophysical, and professional requirements. However, the regulation does not specify the manner in which professional competence must be demonstrated, nor does it restrict the acquisition of competencies exclusively to formal education.

On the other hand, the Adult Education Act introduces education programmes based on learning outcomes and enables the acquisition of micro-qualifications, which are recorded in the relevant registers and serve as official evidence of acquired competencies.

This raises the question of the relationship between the occupational safety and health system and the adult education system, particularly regarding the recognition of competencies acquired through accredited educational programmes.

5. MICRO-QUALIFICATIONS AND DEMONSTRATION OF COMPETENCIES

Micro-qualifications represent a set of competencies acquired through short educational programmes designed to address specific labour market needs. Their development has been encouraged by the European Commission with the aim of increasing the flexibility of education systems and facilitating adaptation to changes in the world of work.

The main characteristics of micro-qualifications include clearly defined learning outcomes, assessment and validation of acquired competencies, alignment of education with labour market needs, and opportunities for rapid reskilling and upskilling [5,8].

Unlike traditional forms of training, micro-qualifications focus on actual work tasks and the competencies required for their safe performance. In the field of occupational safety and health, this is particularly important because it enables educational content to be aligned with the specific risks associated with individual workplaces.

Such programmes often include practical exercises, simulations of workplace situations, and assessments of participants' ability to perform work tasks independently [6,8].

6. CASE STUDY – NON-FORMAL ADULT EDUCATION PROGRAMMES FOR ACQUIRING COMPETENCIES REQUIRED FOR TOWER CRANE OPERATION

An interesting example of the relationship between occupational safety and health and adult education is provided by the case of a worker who completed a non-formal adult education programme for acquiring competencies required for tower crane operation. The programme was identical to the formal micro-qualification programme for tower crane operators. It was delivered by an authorized adult education institution that conducts the micro-qualification programme for tower crane operators based on an approval issued by the Ministry of Science, Education and Youth. The programme included both theoretical and practical training, as well as the assessment of learning outcomes.

Upon successful completion of the programme, the participant was awarded a certificate of competence for tower crane operation, confirming the acquisition of the competencies required to perform the duties of a crane operator. The participant was a foreign worker who did not meet the eligibility requirements for enrolment in the formal micro-qualification programme. During a labour inspection procedure, the question arose as to whether such a certificate constituted sufficient evidence of professional competence for performing jobs with special working conditions.

The case raised several professional and legal issues:

- whether competencies acquired through a non-formal adult education programme for acquiring work-related competencies can be regarded as professional competence,
- the legal status of a certificate issued by an authorized adult education institution,
- whether there is a distinction between a formal qualification and competencies acquired through adult education,

- whether professional competence should be assessed based on the method of acquisition or on verified learning outcomes.

An analysis of the available documentation demonstrated that the programme was identical to a programme approved by the competent ministry and that its learning outcomes, content, and competency assessment methods had been clearly defined. Consequently, the fundamental requirements of the adult education system for demonstrating acquired competencies were fulfilled.

7. LEGAL ANALYSIS OF THE RECOGNITION OF A NON-FORMAL ADULT EDUCATION PROGRAMME FOR ACQUIRING COMPETENCIES REQUIRED FOR TOWER CRANE OPERATION

One of the current issues in the field of occupational safety and health concerns the recognition of competencies acquired through the adult education system as evidence of professional competence for performing jobs with special working conditions. This issue became particularly evident in the case of a foreign worker who, after completing a non-formal programme for acquiring competencies required for tower crane operation, was subject to a labour inspection during which the validity of the issued certificate as proof of professional competence was challenged.

The educational programme was delivered by an adult education institution authorized by the Ministry of Science, Education and Youth to conduct the corresponding formal programme. The non-formal programme included theoretical instruction, practical training, and the assessment of learning outcomes, resulting in the issuance of a certificate confirming the acquisition of competencies required for tower crane operation. The programme clearly defined learning outcomes, participant competencies, and assessment procedures, thereby meeting the requirements of the Adult Education Act and the Croatian Qualifications Framework.

During the inspection procedure, the question arose as to whether the certificate constituted sufficient evidence of professional competence for performing the duties of a tower crane operator. The inspection authority argued that the employer had failed to provide adequate evidence of the worker's professional competence in accordance with occupational safety and health regulations and consequently prohibited the worker from performing the job until appropriate evidence was submitted. Such an interpretation raised important questions regarding the relationship between regulations governing occupational safety and health and those regulating adult education.

From a legal perspective, the key issue is whether professional competence should be understood as a formal qualification or as demonstrated competence for the safe performance of a specific job. Contemporary education systems are increasingly based on the concept of learning outcomes, according to which the decisive factor is what an individual knows, understands, and is able to do upon completion of an educational programme. This principle forms the foundation of the Croatian Qualifications Framework as well as European recommendations on micro-qualifications [4,5,8].

In the present case, the certificate was issued following completion of a non-formal programme that had been developed on the basis of a formal programme approved by the competent ministry. Such a certificate cannot be regarded as a private document without legal significance; rather, it is a

document issued under the public authority granted to an adult education institution. For this reason, it may reasonably be considered credible evidence of acquired competencies, particularly where those competencies have been verified through both theoretical and practical assessment.

An additional argument derives from European lifelong learning policies that promote the recognition of competencies regardless of the manner in which they were acquired. The European Commission and CEDEFOP emphasize that qualification systems should evaluate learning outcomes rather than focusing exclusively on formal educational pathways [5,8]. This approach seeks to enhance labour mobility and improve the responsiveness of education systems to labour market needs.

From the perspective of occupational safety and health, the purpose of the regulatory framework is not to restrict access to particular occupations but to ensure that such work is performed by competent individuals [1,2,6]. If an educational programme provides the acquisition and verification of competencies necessary for the safe operation of work equipment, such competencies should be regarded as relevant evidence of professional competence.

The case discussed in this paper highlights the need for a clearer regulatory definition of the relationship between the adult education system and the occupational safety and health system. Inconsistent interpretation of regulations may create legal uncertainty for employers, educational institutions, and workers, while also hindering the implementation of innovative educational models in practice.

It may therefore be concluded that the further development of non-formal adult education programmes for acquiring work-related competencies will require a more precise definition of their role in demonstrating professional competence for jobs with special working conditions. At the same time, greater emphasis should be placed on the actual knowledge and skills acquired by workers rather than exclusively on the educational pathway through which those competencies were obtained.

8. DISCUSSION

The recognition of competencies acquired through non-formal education represents one of the key issues in contemporary education policy. In the field of occupational safety and health, it is particularly important to maintain a balance between high safety standards and the need for a flexible education system.

From the perspective of occupational safety and health, the most important consideration is whether a worker possesses the competencies required to perform a job safely. If competencies acquired through an accredited programme that includes both theoretical and practical assessment are recognized, it is difficult to identify a professional justification for rejecting competencies acquired through non-formal programmes that are subject to the same theoretical and practical verification procedures.

An additional argument in favour of recognizing micro-qualifications derives from European education policies, which emphasize the importance of learning outcomes rather than exclusively focusing on formal pathways of knowledge acquisition [5,10].

At the same time, it is necessary to ensure:

- uniform criteria for competency assessment,
- an effective quality assurance and supervision system for educational programmes,
- a clear regulatory framework governing the recognition of competencies,
- cooperation between the education system and the occupational safety and health system.

Such an approach may contribute to improving workplace safety, reducing shortages of qualified labour, and enhancing the overall efficiency of the labour market.

9. CONCLUSION

Non-formal education and micro-qualifications are becoming an increasingly important component of contemporary human resource development systems. Their particular value lies in enabling the rapid acquisition of competencies required for the safe and efficient performance of work activities.

The analysis of the legislative framework and the presented case study demonstrates that non-formal adult education programmes may also constitute credible evidence of professional competence for workers performing jobs with special working conditions. Such programmes facilitate the development of practical competencies aligned with labour market needs and occupational safety and health requirements.

For the further development of the system, it is necessary to establish a clearer regulatory framework governing the relationship between the adult education system and the occupational safety and health system in order to avoid differing interpretations of professional competence. The recognition of competencies acquired through non-formal education can make a significant contribution to improving workplace safety, enhancing workforce competitiveness, and promoting a culture of prevention.

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Original scientific paper

PREVALENCE OF MUSCULOSKELETAL DISORDER SYMPTOMS AMONG NURSES IN GOSPIĆ

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Abstract: *Work-related musculoskeletal disorders represent a significant health and occupational challenge in the nursing profession due to high physical demands. This study aimed to determine the prevalence of MSD symptoms across nine anatomical regions among nurses and medical technicians in Gospić (N = 41), representing approximately 40% of the local target population, and to compare them with the general population in Croatia. Data were collected using the Standardized Nordic Questionnaire and analyzed using multivariate logistic regression. The results revealed a higher prevalence of MSD symptoms among nurses across all regions, with the highest rates recorded in the lower back (85.37%), neck (75.61%), and shoulders (58.54%). After adjusting for confounding variables (sex, age, years of service, weekly working hours, weight, and height), only lower back complaints (OR = 3.83; 95% CI 1.43–10.30, p = 0.01) remained significantly associated with the nursing group. In conclusion, nurses in Gospić face an elevated risk of lower back symptoms, emphasizing the critical need for targeted occupational kinesiology interventions.*

Keywords: *statodynamic workloads, work ability, primary prevention, Gospić, Standardized Nordic Questionnaire*

1. INTRODUCTION

The nursing profession is extremely physically demanding, as it involves handling patients and medical equipment, as well as performing numerous movements that require muscular endurance and strength, along with stability and mobility. Significant musculoskeletal and ligament strain is often required, leading to static and dynamic loading of the body, particularly the lumbar spine, resulting in musculoskeletal complaints [1]. Work-related musculoskeletal disorders (WRMSDs) encompass a group of conditions affecting muscles, tendons, nerves, ligaments, joints, soft tissues, and the skeletal system [2]. They arise from repetitive mechanical microtrauma to specific parts of the musculoskeletal system as a consequence of excessive static or dynamic loads that, over time,

exceed the reparative capacity of the tissues [3]. Clinically, they manifest as pain, stiffness, and reduced functional ability, and may range from acute injuries to chronic degenerative conditions [2].

WRMSDs are not limited to healthcare workers but reflect the broader burden of musculoskeletal conditions in the general population. Musculoskeletal disorders account for more than two-thirds of pain-related presentations in primary care [4]. In the European Union, work-related musculoskeletal disorders (WRMSDs) account for as much as 60% of all work-related diseases, most commonly affecting the back [5]. In Croatia, the proportion of musculoskeletal disorders has been steadily increasing, reaching 62.6% in 2013 [5]. WRMSDs represent one of the main causes of early withdrawal from the labor market and rising healthcare costs [6].

International studies consistently confirm the high prevalence of pain among nursing professionals, with a European meta-analysis reporting a prevalence of lower back pain of 61.4% [7]. Research conducted in Croatia confirms similar trends [8]. The aforementioned study recorded an exceptionally high prevalence of pain in the lower back (87.9%), neck (84.5%), and shoulders (81.9%).

Given the high prevalence and diverse manifestations of musculoskeletal disorders, their timely recognition and the identification of associated factors represent an important area of research in public health and occupational medicine. Particular attention is given to nurses and medical technicians in the city of Gospić, whose work involves significant physical strain, as well as to comparisons with the general population in order to better understand the specific characteristics and frequency of symptom occurrence.

Compared with other professions, the prevalence of these disorders among nurses is significantly higher, as confirmed by the results of recent meta-analyses [2]. However, the relationship between the prevalence of MSD symptoms among nurses/medical technicians and the general population remains insufficiently understood. Accordingly, this study is aimed at determining the prevalence of musculoskeletal disorder symptoms among nurses and medical technicians, analyzing their occurrence in different anatomical regions of the body, and examining their relationship with the general population.

2. RESEARCH OBJECTIVES AND HYPOTHESES

Research objectives:

- To determine the prevalence of musculoskeletal disorder symptoms among nurses and medical technicians.
- To determine the association between complaints in different anatomical regions of the body and belonging either to the group of nurses/medical technicians or to the general population.

Research Hypotheses:

- H1. Symptoms of musculoskeletal disorders are present among nurses and medical technicians, with the highest prevalence in the lower back region.
- H2. There is a statistically significant association between the occurrence of musculoskeletal disorder symptoms in different anatomical regions of the body and belonging to the group of nurses/medical technicians.

3. METHODS

The study sample consisted of nurses and medical technicians employed in healthcare institutions in the city of Gospić (N = 41). To assess the prevalence of musculoskeletal disorder symptoms, the online *Standardised Nordic Questionnaire for the Analysis of Musculoskeletal Symptoms* [9] was used. The questionnaire was validated in the Croatian language [10]. For descriptive analysis, frequencies (N) and percentages (%) were used for categorical variables, while arithmetic mean (AM), standard deviation (SD), minimum, and maximum values were used for continuous variables. The normality of the distribution of continuous variables was assessed using the Shapiro–Wilk test. Differences between nurses/medical technicians and the general population were tested using the Mann–Whitney U test for continuous variables and the χ^2 test for categorical variables. The association between group membership and the occurrence of symptoms in different anatomical regions was examined using multivariate logistic regression analysis, with adjustment for potential confounders (sex, age, years of work experience, weekly working hours, body weight, and height).

4. RESULTS AND DISCUSSION

4.1. Sociodemographic and Work-Related Characteristics of the Respondent Sample

The analysis of sociodemographic and work-related characteristics using the chi-square and Mann–Whitney tests (Table 1) showed that nurses/medical technicians and the general population differed significantly in terms of sex (p = 0.0109), years of work experience (p = 0.005), weekly working hours (p = 0.041), and body height (p = 0.014).

Table 1: Descriptive parameters and significance of differences in sociodemographic, work-related, and anthropometric characteristics between nurses/medical technicians and the general population, tested using the Shapiro–Wilk, Mann–Whitney, and chi-square tests.

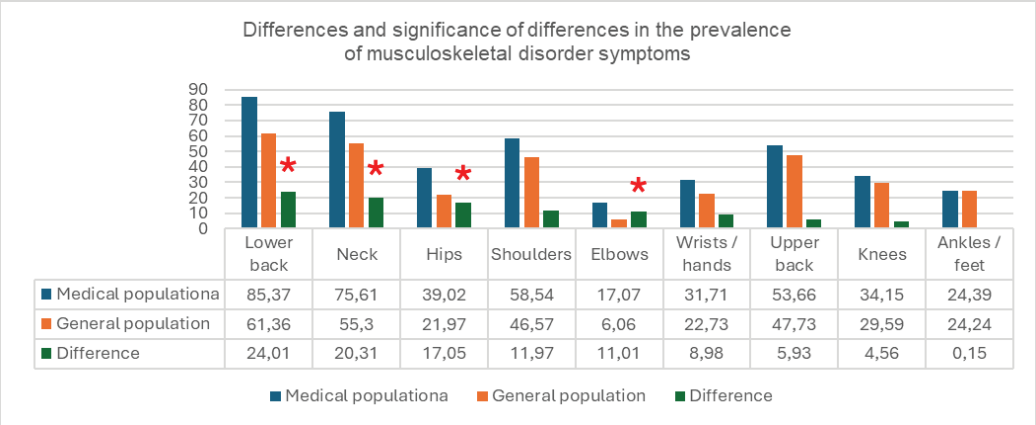
Variables	Nurse	General population	Chi-square	Significance of differences
Sex	36 Ž (88 %) 5 M (12 %)	89 Ž (67 %) 43 M (33 %)	χ^2 = 6,48 p = 0,0109	Statistically significant difference
Dominant hand	90,24 % Right-handers	88,64 % Right-anders	χ^2 = 0,0827 p = 0,7737	Not statistically significant
Variables	**Nurse Mean ± SD Min–Max**	**General population Mean ± SD Min–Max**	**Shapiro-Wilk test**	**Mann-Whitney test**
Age	43,59 ± 10,93 24–64	43,67 ± 9,55 25–66	MP: p = 0,039* GP: p = 0,089	p = 0,909 Not statistically significant
Years of work experience	21,54 ± 10,58 5,25–41	16,13 ± 8,74 5–37	MP: p = 0,018* GP: p < 0,0001*	p = 0,005 Statistically significant
Weekly working hours	41,38 ± SD = 13,57 7,50–80	37,20 ± 12,92 5 – 72	MP: p < 0,0001* GP: p < 0,0001*	p = 0,041 Statistically significant
Body weight	76,67 ± SD = 18,16 57–160	77,61 ± 15,27 48–124	MP: p < 0,0001* GP: p = 0,002*	p = 0,396 Not statistically significant
Body height	168,68 ± 5,80 160–185	172,39 ± 8,71 155–196	MP: p < 0,027* GP: p = 0,141	p = 0,014 Statistically significant
BMI	26,92 ± 6,14 20,81–56,69	25,96 ± 3,87 18,42–39,43	MP: p < 0,0001* GP: p < 0,0001*	p = 0,355 Not statistically significant

Legend: * – non-normal distribution; AM – arithmetic mean; SD – standard deviation; MP – medical population; GP – general population

The group of nurses and medical technicians was predominantly female (88%), which is consistent with data for the nursing profession at the level of the European Union [11]. The nurses in the study had a significantly longer average length of work experience (21.54 years) and worked more hours per week, indicating a higher professional workload and longer-term exposure to occupational demands. The groups did not differ significantly in age or BMI, which reduces the possibility of systematic bias in interpreting differences in health outcomes.

4.2. Prevalence of Symptoms and Critical Body Regions

The results of the study confirmed that nurses and medical technicians had a higher prevalence of symptoms in all nine observed body regions compared with the general population (Figure 1). Using the chi-square test (Figure 1), statistically significant differences were found in the lower back ($p = 0.004$), neck ($p = 0.020$), elbows ($p = 0.0286$), and hips ($p = 0.030$).



	Lower back	Neck	Hips	Shoulders	Elbows	Wrists / hands	Upper back	Knees	Ankles / feet
Medical populationa	85,37	75,61	39,02	58,54	17,07	31,71	53,66	34,15	24,39
General population	61,36	55,3	21,97	46,57	6,06	22,73	47,73	29,59	24,24
Difference	24,01	20,31	17,05	11,97	11,01	8,98	5,93	4,56	0,15

Figure 1. Differences and significance of differences (chi-square test – * statistically significant difference) in the prevalence of musculoskeletal disorder symptoms over the past twelve months by body region in the medical and general population.

These findings, which highlight the lower back and neck as critical regions, are fully consistent with previous research in Croatia [8] and international meta-analyses [7, 12]. The lower back is identified as the most affected region in both groups, suggesting that lumbar complaints are a widespread problem in general; however, among nurses, they are significantly exacerbated by specific occupational demands.

4.3. Results of Multivariate Logistic Regression Analysis

To further examine the association between group membership (nurses/medical technicians vs. general population) and the prevalence of musculoskeletal disorder symptoms, a multivariate logistic regression analysis was performed.

The multivariate logistic regression analysis assessed the association between group membership and the presence of symptoms in nine anatomical regions, with adjustment for potential confounders (sex, age, years of work experience, weekly working hours, body mass, and height). In this way, the odds ratio (OR) was adjusted for the influence of these variables on the association between group membership and symptom occurrence (Table 3). Binary variables were analyzed ("YES" – presence of symptoms, "NO" – absence of symptoms).

The multivariate logistic regression analysis showed that only complaints in the lower back region within the past 12 months (OR = 3.83; 95% CI 1.43–10.30) were significantly associated with belonging to the group of nurses. Other body regions did not show statistically significant differences. This indicates that the medical population has 3.83 times higher odds of experiencing symptoms in the lower back, and that this association is statistically significant (Table 2).

Table 2. Results of multivariate logistic regression for individual anatomical regions

Body region	AOR	95 % CI	p - value	Značajnost (p < 0,05)
Neck	1,99	0,84-4,76	p = 0,12	Not statistically significant
Shoulders	1,28	0,57-2,86	p = 0,54	Not statistically significant
Elbows	2,69	0,67-10,80	p = 0,16	Not statistically significant
Wrists/Hands	0,97	0,39-2,38	p = 0,95	Not statistically significant
Upper back	1,06	0,48-2,33	p = 0,89	Not statistically significant
Lower back	**3,83**	**1,43-10,30**	**p = 0,01**	**Statistically significant**
Hips	1,03	0,41-2,59	p = 0,95	Not statistically significant
Knees	0,75	0,30-1,85	p = 0,53	Not statistically significant
Ankles	0,50	0,18-1,37	p = 0,18	Not statistically significant

Legend: AOR – adjusted odds ratio; CI – confidence interval; OR values > 1 indicate a higher probability of symptom occurrence among nurses compared with the general population

It can be concluded that the population of nurses and medical technicians in the city of Gospić has a statistically significant 3.83-fold higher likelihood of developing WRMSD symptoms in the lower back compared with the general population.

Such results are most likely a consequence of cumulative statodynamic loads among nurses, which include patient handling, prolonged standing, and work in unfavorable ergonomic positions [13]. The nurses in the study had a significantly longer average length of work experience (21.54 years) and worked more hours per week, indicating a higher professional workload and longer-term exposure to occupational demands.

4.4. Role of Preventive Measures

Despite the existence of guidelines, most nurses rarely use available ergonomic aids in daily practice [14]. In addition to biomechanical loading, psychosocial factors such as stress, emotional burden, and job dissatisfaction also significantly influence pain perception and the development of chronic conditions [14].

In the context of primary prevention, occupational kinesiology emphasizes that nurses and medical technicians do not primarily develop musculoskeletal problems because of their work itself, but because they often perform their duties in non-physiological positions and use non-functional movement patterns. While occupational safety systems traditionally focus on ergonomics [14] and the quantification of statodynamic loads (e.g., load weight, number of repetitions) [15], occupational kinesiology, in addition to these aspects, also emphasizes the quality of statodynamic loads, i.e., the correctness of postural and movement habits [16].

The development of WRMSDs is contributed to by occupational demands such as lifting and repositioning patients, as well as unfavorable ergonomic working conditions [13]. For this reason, for the population of nurses and medical technicians, it is critically important to automate correct movement patterns in specific tasks such as lifting, transferring, and lowering patients. If workers'

postural and movement habits are incorrect, they become mechanisms of injury that lead to the accumulation of microtrauma (cumulative trauma), which over time can result in the development of chronic complaints and subsequently a reduction in work capacity.

The formal implementation of occupational kinesiology into the occupational health system for nurses could represent a “win–win–win” situation for 1) nurses/medical technicians, 2) employers, and 3) the state. In this way, nurses and medical technicians would increase the likelihood of preserving musculoskeletal health, employers would benefit from more productive employees with reduced sick leave, while the state would achieve savings in the healthcare system due to a lower number of medical treatments and rehabilitation procedures [17]. Early interventions can reduce sick leave and loss of work productivity among workers with musculoskeletal disorders by more than 50%; reduce healthcare costs by up to two-thirds; reduce disability benefit costs by up to 80%; reduce the risk of permanent work disability and job loss by up to 50%; and reduce the risk of developing various mental disorders as well as comorbidities [18]. Given that the sample from Gospić includes a large proportion of the local nursing workforce, these results provide a credible insight into the local context and emphasize the need for urgent implementation of preventive measures and education.

Limitations of the study include the use of self-reported data, which may lead to subjectivity and reporting bias. The sample of nurses and medical technicians from the city of Gospić limits the generalizability of the results to a broader population; however, it includes approximately 40% of the target group, ensuring high representativeness within the local context. The obtained findings provide valuable insight into musculoskeletal health in this setting and may serve as a basis for further research and the development of preventive measures. Additionally, differences between groups in demographic and work-related characteristics represent potential confounding factors, which were accounted for using logistic regression; therefore, the results should be interpreted with caution, particularly regarding causality.

5. CONCLUSION

This study confirms a high prevalence of musculoskeletal disorder symptoms among nurses and medical technicians in Gospić compared to the general population, with the lower back and neck identified as the most critical anatomical regions. Even after adjusting for potential confounding variables, belonging to the nursing group remains a strong independent risk factor specifically for lower back complaints, with nurses exhibiting a 3.83-fold higher likelihood of developing symptoms.

These findings highlight the critical need for systemic preventive measures within the healthcare sector. Rather than relying solely on traditional ergonomic standards, future interventions should integrate occupational kinesiology principles to automate correct movement patterns during physically demanding tasks like patient handling. Implementing such targeted training programs represents a highly cost-effective strategy to preserve healthcare workers' musculoskeletal health, reduce sick leave, and minimize long-term healthcare costs.

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Original scientific paper

DIFFERENCES IN THE DEGREE OF EXPOSURE OF NURSES TO OCCUPATIONAL RISKS BETWEEN PUBLIC AND PRIVATE HEALTH INSTITUTIONS IN THE REPUBLIC OF NORTH MACEDONIA

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Abstract: *The number of healthcare workers in the world is estimated at around 104 million, of which 29.8 million are nurses who are exposed to occupational risks on a daily basis. This paper investigates the state of occupational safety in public and private healthcare in Republic of North Macedonia.*

The main problem and goal, as well as the main hypothesis of this research, was to discover whether there are differences in the exposure to occupational risks and the application of preventive measures in the work of nurses in public and private healthcare institutions. The results of the research showed that occupational risks are present to a greater extent in public healthcare institutions compared to private healthcare institutions, indicating an urgent need for a systemic approach to improve the working environment in public healthcare institutions..

Keywords: *Occupational risk, nurses, public and private healthcare institutions*

1. INTRODUCTION

According to the World Health Organization (WHO) data from 2020, the number of health workers in the world is estimated at around 104 million, of which 29.8 million are nurses [1]. Due to the demanding nature of the work and the environment in which it is performed, nurses are exposed to a high occupational risk of occupational injuries and illnesses, which, in addition to affecting the well-being and health of nurses, also entail significant costs for the employer in terms of financial compensation, lower productivity and absenteeism [2]. The healthcare sector has undergone numerous changes in the last few decades, with demographic, epidemiological, social, cultural and technological changes leading to a number of new challenges that the field of occupational safety and health needs to address. The shortage and aging of the healthcare workforce, as well as the

insufficient number of new employees, the increasing number of chronically ill patients and the large number of new technologies are affecting changes in the work system and work environment of healthcare workers, namely nurses, which directly affects their well-being and health [3].

The importance of protecting the health and safety of workers in the health sector was recognized by WHO as early as 2007, when 193 Member States endorsed the Worker's health: global plan of action (GPA) and thereby adopted a ten-year plan in which they would develop national programs for the protection of the health and safety of workers in the health sector, in order to preserve and improve health and prevent and reduce occupational accidents, work-related injuries, occupational diseases and work-related illnesses, and in order to reduce economic losses [4], [5], [6]. The employer is responsible for the safety and health of workers while performing work at the workplace, and his task is to provide a healthy workplace, i.e. a workplace that is free from harm to the health of workers. Due to this provision, the employer is obliged to prepare a risk assessment that determines the risk of injury and damage to health that a particular workplace carries and the risk of exposure to a particular hazard or group of hazards [7].

In the Republic of North Macedonia, occupational safety and health protection are regulated by two basic laws: the Law on Occupational Safety and Health and the Law on Health Protection. According to these laws, occupational diseases and injuries, their diagnosis, recording and treatment are under the responsibility of the selected physician (general practitioner) in case of injury or suspected illness. An occupational medicine specialist is solely authorized to diagnose an occupational disease, assess work capacity and participate in the rehabilitation process, while the Health Insurance Fund of the Republic of North Macedonia is responsible for financial coverage of treatment and rehabilitation [8].

Given the high risk of occupational injuries and illnesses among nurses, the question arises as to what are the most common occupational risks encountered by this category of healthcare workers and what preventive measures are applied in our healthcare system in order to reduce workplace-related injuries and illnesses among nurses. Since research [9], [10], [11], [12] examining various aspects of occupational health and safety in the public and private healthcare sectors suggests that private and public healthcare institutions differ in terms of nurses' exposure to occupational risks, as well as in terms of the application of preventive measures, this paper will investigate the state of occupational safety in public and private healthcare in our country. All this because healthy nurses are a key factor in ensuring close monitoring of patients, providing empathy and patient-centered care.

2. RESEARCH RESULTS AND ANALYSIS

The main problem and objective of this research is: Are there differences in the exposure to occupational risks and the application of preventive measures in the work of nurses in public and private healthcare institutions?

The main hypothesis should show whether there are differences in the degree of exposure of nurses to occupational risks between public and private healthcare institutions.

The research sample consists of 120 nurses, 60 of whom are from public health institutions and 60 from private health institutions. The respondents are of both sexes, aged 20-64, with different levels of education, regularly employed in different departments, i.e. services, with more than 1 year

of work experience. The research used a questionnaire for demographic and professional data, and the collected data were processed and analyzed with the SPSS software package.

Here are presented the research results that relate to the comparisons between public and private healthcare institutions regarding the application of preventive measures related to the occupational risks to which nurses are exposed during their work. The obtained results are aimed at verifying the truth of the main hypothesis

Table 1 shows the descriptive statistical results for the prevalence of physical occupational risks in public and private healthcare institutions, as perceived by nurses, while Table 2 contains the results of the t-test for the statistical significance of the differences in the arithmetic means between the two groups, which is aimed at verifying the truth of the main hypothesis.

Table 1: Descriptive statistics on the prevalence of physical occupational risks in public and private healthcare institutions

Group statistics					
	Sector	**N**	**Mean**	**Std. Deviation**	**Std. Error Mean**
Physical risks	Public health institutions	60	18,22	1,303	,168
	Private health institutions	60	16,58	1,441	,186

Table 2: Difference between public and private healthcare institutions in the prevalence of physical occupational risks among nurses

Independent samples test										
		Levene's Test for Equality of Variances		**t-test for Equality of Means**						
		F	**Sig.**	**t**	**df**	**Sig. (2-tailed)**	**Mean Differen.**	**Std. Error Differen.**	**95% Confidence Interval of the Difference**	
									Lower	**Upper**
Physical risks	Equal variances assumed	,404	,526	6,511	118	,000	1,633	,251	1,137	2,130
	Equal variances not assumed			6,511	116,819	,000	1,633	,251	1,137	2,130

Table 3 shows the descriptive statistical results for the prevalence of chemical occupational risks in public and private healthcare institutions in the work of nurses, and Table 4 shows the result of the t-test for the statistical significance of the differences in the arithmetic means between the two groups of respondents.

Table 3: Descriptive statistics on the prevalence of chemical occupational risks in public and private healthcare institutions

Group statistics					
	Sector	N	Mean	Std. Deviation	Std. Error Mean
Chemical risks	Public health institutions	60	19,90	1,399	,181
	Private health institutions	60	15,95	1,501	,194

Table 4: Difference between public and private healthcare institutions in the prevalence of chemical occupational risks among nurses

Independent samples test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Differen.	Std. Error Differen.	95% Confidence Interval of the Difference	
									Lower	Upper
Chemical risks	Equal variances assumed	,259	,612	14,916	118	,000	3,950	,265	3,426	4,474
	Equal variances not assumed			14,916	117,420	,000	3,950	,265	3,426	4,474

Table 5 contains the descriptive statistics on the prevalence of biological occupational risks in public and private healthcare institutions in the work of nurses. Table 6 shows the result of the t-test for the statistical significance of the differences in arithmetic means between respondents from different sectors.

Table 5: Descriptive statistics on the prevalence of biological occupational risks in public and private healthcare institutions

Group statistics					
	Sector	N	Mean	Std. Deviation	Std. Error Mean
Biological risks	Public health institutions	60	17,22	1,485	,192
	Private health institutions	60	14,10	1,570	,203

Table 6: Difference between public and private healthcare institutions in the prevalence of biological occupational risks among nurses

Independent samples test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Differen.	Std. Error Differen.	95% Confidence Interval of the Difference	
									Lower	Upper
Biological risks	Equal variances assumed	,002	,961	11,170	118	,000	3,117	,279	2,564	3,669
	Equal variances not assumed			11,170	117,641	,000	3,117	,279	2,564	3,669

Table 7 shows the group descriptive statistics for the prevalence of ergonomic occupational risks in public and private healthcare institutions in the work of nurses, while Table 8 shows the result of the t-test for the statistical significance of the differences in arithmetic means between respondents from different sectors.

Table 7: Descriptive statistics on the prevalence of ergonomic occupational risks in public and private healthcare institutions

Group statistics					
	Sector	N	Mean	Std. Deviation	Std. Error Mean
Ergonomic risks	Public health institutions	60	19,95	1,419	,183
	Private health institutions	60	13,93	1,506	,194

Table 8: Difference between public and private healthcare institutions in the prevalence of ergonomic occupational risks among nurses

Independent samples test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Differen.	Std. Error Differen.	95% Confidence Interval of the Difference	
									Lower	Upper
Ergonomic risks	Equal variances assumed	,121	,728	22,525	118	,000	6,017	,267	5,488	6,546
	Equal variances not assumed			22,525	117,592	,000	6,017	,267	5,488	6,546

Table 9 presents the group descriptive statistics for the prevalence of psychosocial occupational risks in public and private healthcare institutions. Table 10 contains the results of the t-test for the statistical significance of differences in arithmetic means between respondents from different healthcare sectors.

Table 9: Descriptive statistics on the prevalence of psychosocial occupational risks in public and private healthcare institutions

Group statistics					
	Sector	N	Mean	Std. Deviation	Std. Error Mean
Psychosocial risks	Public health institutions	60	19,67	1,526	,197
	Private health institutions	60	17,00	1,484	,192

Table 10: Difference between public and private healthcare institutions in the prevalence of psychosocial occupational risks among nurses

Independent samples test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Differen.	Std. Error Differen.	95% Confidence Interval of the Difference	
									Lower	Upper
Psychosocial risks	Equal variances assumed	,072	,789	9,704	118	,000	2,667	,275	2,122	3,211
	Equal variances not assumed			9,704	117,911	,000	2,667	,275	2,122	3,211

The results of all 5 t-tests for the statistical significance of the difference in arithmetic means between public and private healthcare institutions in terms of the prevalence of occupational risks in the work of nurses showed that occupational risks are present to a higher extent in public healthcare institutions compared to private healthcare institutions. This confirms the truth of the main hypothesis.

3. CONCLUSION

According to previous research and data from the World Health Organization (WHO), the number of healthcare workers in the world is estimated at around 104 million, of which 29.8 million are nurses who are exposed to occupational risks on a daily basis. This paper investigates the state of occupational safety in public and private healthcare in our country.

The main problem and objective of this research was: Are there differences in the exposure to occupational risks and the application of preventive measures in the work of nurses in public and private healthcare institutions?

The main hypothesis was to prove whether there are differences in the degree of exposure of nurses to occupational risks between public and private healthcare institutions.

The results of the research showed that occupational risks are present to a greater extent in public healthcare institutions compared to private healthcare institutions, thus confirming the truth of the main hypothesis.

The results obtained in this way indicate an urgent need for a systemic approach to improving the working environment in public health institutions, which have a higher level of occupational risks and a lower application of preventive measures, so that they must be treated as priority areas for intervention in occupational health and safety policies.

It is also advisable to use qualitative methods for a deeper understanding of the perceptions and experiences of nurses in relation to occupational risks and preventive practices.

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Professional paper

NATIONAL REGISTRIES OF WORKERS OCCUPATIONALLY EXPOSED TO CARCINOGENIC, MUTAGENIC AND REPROTOXIC SUBSTANCES AND ANTINEOPLASTIC DRUGS IN CROATIA

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Abstract: *Occupational exposure to carcinogenic, mutagenic, and reprotoxic (CMR) substances represents a significant public health concern that requires systematic monitoring and long-term health surveillance of exposed workers. In Croatia, employers are required under national occupational safety and health legislation to report workers exposed to hazardous substances to the Croatian Institute of Public Health (CIPH). Since 2010, the CIPH has maintained a registry of exposed workers. Based on the collected data, the CIPH prepares educational programmes aimed at raising awareness of the risks associated with exposure to these substances. A separate registry is also maintained for healthcare and laboratory personnel handling antineoplastic drugs (ADs), which are also classified as CMR substances. This paper presents an overview of both registries.*

Keywords: *occupational exposure, CMR substances; antineoplastic drugs; registry*

1. INTRODUCTION

Many substances used in workplace processes can have adverse effects on human health. Insufficient awareness of chemical hazards and non-compliance with occupational health and safety measures may result in injuries and occupational diseases among workers handling these substances. For educational purposes and to facilitate the exercise of certain workers' rights, the Department of Occupational Health of the Croatian Institute of Public Health (CIPH) maintains registries of workers exposed to carcinogenic, mutagenic, and reprotoxic (CMR) substances, as well as workers exposed to antineoplastic drugs (ADs).

2. LEGAL AND REGULATORY FRAMEWORK

In accordance with Article 131 of the Health Care Act, the CIPH is responsible, among other duties, for maintaining registries of workers exposed to specific occupational hazards [1]. The Ordinance on the Protection of Workers from Exposure to Hazardous Substances at Work, Occupational Exposure Limit Values and Biological Limit Values further requires the maintenance of registries on workers exposed to chemical hazards in the workplace and the reporting of such exposures to the competent authorities [2].

Accordingly, the CIPH has maintained a registry of workers exposed to carcinogenic and mutagenic substances since 2010. Since 2023, this registry has also included workers exposed to reprotoxic substances.

The CIPH also maintains a separate registry of workers exposed to ADs. Although ADs are medicinal products rather than substances, as defined by the Medicinal Products Act, their active ingredients are chemical substances that frequently exhibit CMR properties. While these substances are intended to target malignant cells, they may also affect healthy cells. In recognition of the potential acute and chronic health effects associated with occupational exposure, the CIPH maintains registries of healthcare workers employed in hospital departments where ADs are prepared or administered.

3. METHODOLOGY

The registration procedure is as follows: employers download the registration form from the CIPH website, complete it and submit it to the CIPH by email or post. The collected information includes details on the employer's activities, worker demographics (age and sex), the substances used, the processes in which they are used and the quantities involved. Information is also collected on the nature and duration of occupational exposure to CMR substances, as well as the personal protective equipment (PPE) used. In addition, data from workers' occupational health examinations are recorded.

Similar information is collected for the registry of workers exposed to ADs. This includes details on the employer, worker demographics (age and sex), the ADs prepared or administered, the routes and circumstances of occupational exposure and the protective measures implemented to reduce exposure.

4. DISCUSSION

The interpretation of both registers is based on a descriptive analysis of data from the registers. The data collected through these registries are presented in the annual report of the Department of Occupational Health of the CIPH and are used to develop educational lectures organized by the Department. In addition, the registries serve as a valuable resource in the recognition and verification of occupational diseases.

Despite ongoing efforts to encourage employers to register workers exposed to CMR substances and ADs, participation remains unsatisfactory. The registry of workers exposed to CMR substances

includes between 46 and 190 workers annually. Unfortunately, only a small number of employers recognize the importance of registering exposed workers and the number of participating employers has declined over time. Currently, the registry contains data from only five employers. By comparison, data from the European Agency for Safety and Health at Work indicate that nearly 50% of the European Union workforce is likely exposed to at least one carcinogenic risk factor, including CMR agents [3].

Most workers registered in the CMR registry are employed in the manufacturing sector and are exposed to a single CMR substance during their work. Although some workers may be exposed to multiple CMR substances, such exposure is generally limited to accidental or incident-related situations.

At present, 990 workers employed in 22 healthcare institutions are registered in the AD exposure registry. The occupational groups with the highest levels of exposure are nurses working in oncology and haematology departments and pharmacy technicians involved in the preparation of ADs according to physicians' prescriptions. Occupational exposure to ADs is a well-recognized issue across Europe, with an estimated 12.7 million healthcare professionals—predominantly nurses and pharmacy technicians—potentially exposed to hazardous medicinal products [4]. One of the major challenges in protecting healthcare workers is the lack of centralized preparation of these hazardous drugs.

A further concern is near absence of cleaning personnel from both registries. These workers are rarely identified and registered by employers, despite evidence that inadequate awareness of contamination risks may contribute to the spread of hazardous substances across multiple work surfaces, thereby increasing the number of potentially exposed workers.

5. CONCLUSION

Many substances, as well as ADs, pose significant risks to human health. Workers are often not fully aware of the hazards associated with occupational exposure to these substances. Nevertheless, employer participation in the registries of exposed workers remains limited. Beyond facilitating the recognition of occupational diseases and safeguarding workers' rights, the data collected through these registries provide an important basis for developing targeted educational lectures for workers, occupational safety professionals, employers and their representatives.

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Professional paper

A NOTE ON PROFESSIONAL RISKS IN AGRICULTURAL TRACTOR OPERATIONS

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Abstract: *Despite technological developments, agriculture remains one of Europe's most hazardous sectors, recording hundreds of fatalities and thousands of non-fatal accidents annually. Tractor operations, in particular, present significant occupational risks and are associated with a substantial portion of these accidents. In Portugal, these risks are compounded by a prevalence of micro-enterprises that often lack resources for safety training, a situation further exacerbated by an aging workforce. As a result, improving the way occupational risks are communicated to workers has become a critical component of accident prevention. In this context, the present paper analyses how a safety awareness video addressing tractor rollover accidents can support risk communication and contribute to safer agricultural practices.*

Keywords: *Accident prevention, agriculture, occupational safety, risk management.*

1. INTRODUCTION

Increasing investment in health and safety at work promotion has been reflected in reduced accident rates across all sectors of activity. While the primary purpose of the investment is obviously to positively impact the health and well-being of workers, it is important to recognize that a safe and healthy work environment is a decisive factor for the success of organizations/companies. Therefore, investment in measures that enhance the safety and health of workers plays a crucial role in the competitiveness of organizations/companies [1].

The accidents involving agricultural tractors have received some attention in the literature, with studies from different countries focusing on various aspects of this problem. ([2] presents a systematic review on machine and equipment injuries). Studies and statistics identify workplace accidents in tractor operation as a continuing issue involving numerous variables, particularly relevant when

considering factors such as worker age or attitudes [3]. A high incidence is observed among older agricultural workers, often affected by health vulnerabilities and risky practices associated with the improper/non-existent use of rollover protection structures (ROPS). These factors, combined with adverse environmental/surrounding conditions (uneven terrain, steep slopes, …) explain a significant portion of this type of accident [4].

One possible approach to overcome limitations is the incorporation of Risk Management systems into daily agricultural operations, since this systematic process plays a crucial role in reducing human error and influences positive safety behaviour, by identifying, quantifying, and mitigating workplace hazards to prioritize the implementation of preventive measures [5]. Beyond simple compliance with legal requirements, risk assessment fosters a proactive organizational culture that prioritizes prevention, continuous improvement, and employee engagement by communicating these assessments directly to workers, but not easy to implement because of several structural, economic, and behavioural barriers that characterize the agricultural sector. To bridge this gap, video communication emerges as a transformative tool capable of translating abstract risk assessments into immediate, accessible, and emotionally resonant knowledge. By replacing dense text manuals with dynamic visual storytelling, videos effectively overcome literacy barriers and simplify complex spatial hazards, such as tractor rollovers. Because farming routines are highly dictated by intense seasonal workloads, short and friendly video content acts as a practical micro-learning solution. Ultimately, delivering high-quality, visual guidance directly to farmers via accessible digital platforms transforms risk communication from a passive legal requirement into an engaging, life-saving habit that promotes lasting behavioural change.

In Portugal, although workplace accidents in agriculture, specifically those involving tractor operation, represent a serious occupational safety issue, the literature remains somewhat scarce. Although there is a legal framework for occupational safety in the use of tractors, evidence points to gaps associated with enforcement and deficiencies in specific training in the sector.

In this work, we reflect on the risks associated with tractor operation, analysing a safety awareness video available on the website of the Portuguese Authority for Working Conditions (Autoridade para as Condições do Trabalho - ACT), the national body responsible for occupational safety and health. We examine how the content of the video relates to the main occupational hazards identified in the literature (e.g. [6])., and highlight the educational value of the video as a risk communication and prevention tool, and its contribution to improving risk perception, promoting safer work practices, and reinforcing safety culture among tractor operators.

The paper is organized as follows. Section 2 highlights the role of risk assessment in improving working conditions and reducing occupational accidents and diseases. Section 3 focuses on risks associated with tractor operation. Section 4 presents a reflective analysis of a tractor rollover safety awareness vídeo. Finally, Section 5 presents the concluding remarks.

2. RISK ASSESSMENT

Occupational risk management has evolved from a compliance-based activity into a strategic process aimed at improving both worker safety and organizational performance. Central to this process is risk assessment, which involves the identification of hazards, the evaluation of their potential consequences, and the prioritization of preventive measures [7]. Systematic risk assessment has been recognized as an important tool for reducing occupational accidents and work-related

diseases, particularly in small and medium-sized enterprises [8], and in the agricultural sector, it is especially relevant due to the combination of environmental, mechanical, and human factors that contribute to workplace accidents. Tractor operation, in particular, is associated with hazards such as rollovers, mechanical failures, inadequate maintenance, and unsafe operator behaviours. Following risk identification, preventive measures should be implemented according to the hierarchy of controls, where hazard elimination and engineering controls are preferred, complemented by administrative measures, training, and safe work practices [9]. In the context of tractor safety, examples include the use of ROPS, restraint systems, and operator training.

Engineering and organizational controls are essential in preventing tractor-related accidents, but their effectiveness depends largely on workers´ awareness and understanding of occupational risks. Consequently, communication and training tools have become increasingly important components of risk management systems. Educational videos, by presenting realistic work situations and preventive measures in a visual and accessible format, can enhance risk perception, support safer behaviours, and contribute to the development of a stronger safety culture. This is particularly relevant in agriculture, where work is often performed in isolated environments and access to formal training may be limited.

3. RISKS ASSOCIATED WITH TRACTOR OPERATION

There are a wide range of risk factors associated with agricultural machinery operation. In [10], the authors identified several risks involved in agricultural tractor operations, such as:

- tractor rollovers,
- run overs,
- lack of safety devices,
- non-use of restraint systems,
- inadequate maintenance practices,
- operation under adverse conditions,
- insufficient operator training,
- other.

Among these factors, tractor rollovers deserve particular attention because they are frequently associated with severe injuries and fatalities, representing one of the leading causes of death in agricultural work. Since tractor accidents rarely result from a single cause, emerging from complex interactions between unsafe behaviours and unsafe conditions, within this dynamic, insufficient operator training stands out as a critical, constituting a factor that directly drives behavioural errors and magnifies mechanical and environment risks.

In this context, safety training and awareness tools, such as educational videos, play an important role in occupational risk management. Their value lies not only in transmitting technical information but also in promoting risk perception, encouraging safe behaviour, and strengthening safety culture among operators. Visual resources allow workers to observe realistic situations, understand the consequences of unsafe practices, and identify preventive actions more effectively than traditional written instructions.

4. ANALYSIS OF A SAFETY AWARENESS VÍDEO: TRACTOR ROLLOVER

Video Technical Information

- Title: *Esmagamento por reviramento de trator* (Tractor rollover crushing)
- Topic: Workplace accident investigation involving a fatal tractor rollover in an olive grove
- Format: Practical case study analysis including context, causes, and preventative measures
- Language: Portuguese
- Link: *https://youtu.be/WPu3mJNJygs?si=DyzHiOEFcusiRR6s*
- Duration: 5' 4''



Figure 1: Workplace safety video analysing tractor crushing/rollover risks
Source: *Esmagamento por reviramento de trator* [11]

Context

The video reconstructs a fatal workplace accident (during olive harvesting operations). On the day of the incident, the tractor was exhibiting mechanical issues. While operating on a steep slope and irregular terrain, the driver accelerated to avoid ground workers in his path. Due to the uneven terrain and the wheel climbing the tree base, the tractor rolled over. The operator was not wearing a seat belt, was thrown inside the cabin, and was fatally crushed as the cabin structure collapsed.

Witness testimonies and post-accident technical inspections revealed several critical failures:

- Human Factor: The driver failed to use the seat belt or any alternative operator restraint system. His training and safety information were inadequate for the specific tasks he was performing.

- Mechanical Factor: The tractor suffered from a severe lack of maintenance, resulting in malfunctioning hydraulic systems and compromised brakes
- Organizational Factor: The company officially maintained an updated risk assessment and prevention plan on paper, but it was not effectively implemented in daily operations.

The fatality could have been entirely prevented through basic safety compliance:

- Restraint Systems: If the driver had been using a seat belt, he would have remained secure inside the protective structure,
- Stability Awareness: Since tractors possess a high center of gravity, operators must receive specific training to understand machinery limits on sloped or irregular terrains to prevent losing stability
- Strict Maintenance: Machinery must undergo regular servicing, adjustments, and cleaning to eliminate technical failures in steering, braking ,…, which are frequent triggers for rollovers.

The accident reconstruction presented in the video demonstrates that tractor rollovers are rarely the consequence of a single failure. Instead, they result from the interaction of human, mechanical, environmental, and organizational factors. In the analysed case, inadequate maintenance practices reduced the tractor's operational reliability, while the absence of a seat belt exposed the operator to fatal consequences during the rollover event. These factors were further aggravated by difficult terrain conditions and by shortcomings in the practical implementation of occupational safety measures. From a risk management perspective, the video addresses several levels of the hierarchy of controls.

Beyond its educational content, the video illustrates how audiovisual communication can contribute to occupational risk prevention. By combining the reconstruction of a real accident with an explanation of its underlying causes, the resource facilitates risk perception and transforms abstract safety recommendations into concrete and recognizable situations. This characteristic is particularly important in agriculture, where workers are frequently exposed to dynamic work environments and may have limited access to formal training programmes.

The video therefore functions not only as a source of information but also as a risk communication tool capable of supporting behavioural change. By improving awareness of the mechanisms that lead to tractor rollovers and by reinforcing preventive measures, such audiovisual resources may contribute to strengthening safety culture and reducing the incidence of serious accidents in agricultural operations.

3. CONCLUSION

Tractor-related accidents remain one of the leading causes of severe and fatal injuries in agriculture, making their prevention a priority within occupational safety and health policies in the sector.

The video analysed in this study reinforces key preventive principles related to tractor safety, including training, compliance with operating procedures, correct use of seat belts and ROPS, and awareness of environmental hazards. While educational interventions cannot replace engineering or organizational controls, they can improve risk perception and reduce behavioural risk factors.

By linking safety requirements to real working situations, the video supports safer behaviours and contributes to accident prevention, particularly in agricultural contexts characterized by small enterprises, ageing workers, and limited access to formal training.

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Review article

THE IMPACT OF NIGHT WORK ON THE HEALTH OF NURSES

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Abstract**:** *Nurses and medical technicians employed in healthcare institutions are inevitably exposed to night work as a permanent feature of their profession. Long-term exposure to shift work, particularly night shifts, is associated with a range of potentially harmful effects on employees' physical and mental health. These effects are not only reflected in the well-being of healthcare workers but may also impact the quality and safety of care they provide to patients. The aim of this paper was to review the impact of night work on sleep quality, physical and mental health, and work performance of nurses and medical technicians. Based on recent scientific findings, night work significantly affects multiple aspects of nurses' health and functioning.*

Keywords: *health, night work, nurses, prevention*

1. INTRODUCTION

The modern healthcare system is based on the continuous provision of care 24 hours a day, including night shifts, weekends, and public holidays. Owing to the nature of their work, nurses and medical technicians are among the professions most exposed to prolonged shift and night work.

Night work plays an important role in ensuring continuous patient care, monitoring patients' health status, administering therapy, and providing emotional support.

Although night work is an indispensable part of the healthcare system, numerous studies warn of its negative consequences for the physical and mental health of healthcare workers. Working night shifts is associated with increased fatigue, sleep disturbances, reduced concentration, and a higher risk of occupational errors, which may also affect patient safety [1]. An additional problem is posed by irregular work schedules and insufficient time for rest, which hinder the body's adaptation to shift work.

It is estimated that between 15% and 33% of workers worldwide are engaged in some form of shift work, while in the healthcare system these proportions are considerably higher owing to the need for the uninterrupted provision of care [2]. A particular challenge is the fact that the majority of nurses are women who, in addition to their professional obligations, often also bear numerous family responsibilities. Such circumstances further hinder recovery after night shifts and the maintenance of a balance between work and private life.

For all these reasons, studying the impact of night work on the health of nurses and medical technicians is important for improving working conditions, preserving the health of healthcare workers, and ensuring the quality and safety of care. The aim of this paper is to present current knowledge on the impact of night work on the physical and mental health of nurses and medical technicians and to highlight possible measures for prevention and health protection.

2. NIGHT WORK IN NURSING

2.1. Definition and Legal Framework of Night Work

To understand the impact of night work on health, it is first necessary to define the concept of night work itself and to analyse its legal and professional determinants. Although night work is most often described as work performed during the night, its definition varies across legal systems and international organisations.

In the Republic of Croatia, night work is defined in Article 69 of the Labour Act as work performed between 10 p.m. and 6 a.m., lasting at least seven hours [3]. While this definition clearly delineates the time frame of night work, it does not take into account individual differences among workers or the specific health requirements of particular medical professions.

The working conditions of healthcare workers, including nurses and medical technicians, are further regulated by the Collective Agreement for the Healthcare and Health Insurance Sector [4]. However, even this regulation does not fully address all the health risks associated with prolonged work on night shifts.

The health consequences of night work have been particularly emphasised by the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC). In 2020, the IARC classified night shift work as probably carcinogenic to humans, owing to a possible increase in the risk of developing malignant diseases [5]. This assessment is based on limited but growing epidemiological evidence in humans and on sufficient evidence from animal studies, which point to an association between prolonged night work and an increased risk of developing certain types of cancer, particularly breast cancer and colorectal cancer [5].

3. CONSEQUENCES OF NIGHT WORK

3.1. Health Consequences of Night Work

Cardiovascular and metabolic risks associated with night work, together with sleep disturbances and cognitive difficulties, are among the most serious health consequences of prolonged shift work and have been studied for decades. Research shows that night work not only causes fatigue and sleep difficulties but also disrupts essential bodily functions, which gradually deteriorate the longer one is exposed to this mode of work [6].

Numerous cardiovascular changes have been observed in nurses working night shifts, independently of other risk factors such as smoking or physical inactivity [7]. These changes are considered to result primarily from the prolonged disruption of the circadian rhythm, that is, the natural sleep–wake cycle [7].

The health consequences of night work most often first manifest as sleep disturbances. Among the most common symptoms are insomnia, excessive daytime sleepiness, and circadian rhythm disorders [8]. The problem is not exclusively biological in nature, however, but also involves psychosocial factors such as family obligations, household noise, and the inability to secure adequate conditions for sleeping during the day [8]. A nurse who finishes work in the morning after a night shift does not return to a quiet, darkened environment suited to rest, but to a daily routine marked by daytime activities, noise, and exposure to light. As a result, the body often fails to recover fully between shifts, particularly in the case of prolonged work on night shifts.

The consequences of chronic exposure to night work are also evident in the area of cognitive health. Research shows that nurses who work rotating night shifts for eleven or more years have twice the risk of developing mild cognitive impairment compared with those who work day shifts exclusively, and a higher incidence of dementia is also recorded [6].

Night work is also associated with an increased risk of developing metabolic disorders. A meta-analysis encompassing nearly half a million participants showed that individuals who work night shifts have an approximately 30% higher risk of developing type 2 diabetes compared with workers employed on day shifts only [9]. One of the main physiological mechanisms contributing to the increased cardiovascular risk is the absence of the expected nocturnal fall in blood pressure, known as “night dipping”. In healthy individuals, blood pressure physiologically decreases by 10–20% during the night, allowing the heart and blood vessels the rest they require [9]. Research shows that individuals who work night shifts often have abnormal blood pressure values and lack this physiological nocturnal decline [5].

Sleep deprivation associated with night work is considered one of the important factors in the development of depressive symptoms and anxiety among nurses and medical technicians [8]. There is, moreover, a bidirectional relationship between sleep quality and mental health — poor sleep increases the risk of depression, while depression further impairs sleep quality [8]. A systematic review and meta-analysis covering twenty studies and a total of 37,983 participants over a period of thirty years confirmed a higher prevalence of depression among nurses working night shifts [10].

3.2. Work Performance and Patient Safety

The performance of nurses during night shifts largely depends on their health status and general well-being, as it directly affects patient safety, the quality of care, and the functioning of the entire healthcare system. Nurses who work at night represent a group at increased health risk, as well as a potential source of errors that may have serious medical consequences.

A literature review encompassing 38 scientific papers showed that in 82% of the studies fatigue was identified as the main cause of medication administration errors [11]. It was established that fatigue associated with night work is directly linked to reduced cognitive performance, impaired attention, and a lower level of alertness — all of which are key prerequisites for the safe administration of therapy [11].

According to data from the World Health Organization, medication administration errors are the leading global cause of harm related to health care and incur an annual cost of approximately 42 billion US dollars [11]. Nurses who work rotating night shifts report a considerably poorer subjective assessment of their own work performance at night compared with day shifts, citing fatigue, reduced concentration, and slower decision-making as the most important factors [11].

Particularly concerning is the fact that nurses are aware of the decline in their own performance yet at the same time feel powerless, because night shifts are an unavoidable part of their profession. Such findings clearly indicate that investing in the protection of nurses' health is not merely a matter of humanity and the quality of working conditions, but also an important economic and safety dimension of the healthcare system.

Objective measurements of predicted cognitive effectiveness during 12-hour shifts have shown that, in nurses working night shifts, a significant decline in cognitive abilities occurs in the later hours of work — precisely in the period when the risk of errors is greatest [12]. It was established that this decline is not merely a subjective sense of fatigue and exhaustion, but can be reliably measured and predicted using statistical methods, which opens up the possibility of developing preventive measures, for example by monitoring brain activity during work [12].

Table 1 shows the most common types of errors associated with fatigue during nurses' night work, as well as the mechanisms by which they arise.

Table 1: Overview of adverse events and errors associated with night work among medical staff, based on sources [11], [12], and [13]

Type of error / adverse event	Mechanism of occurrence	Frequency / risk
Medication administration errors	Reduced attention, fatigue, poorer concentration	Risk is 82% higher when fatigue is present
Patient falls	Slower response, reduced alertness	Occur more frequently at night
Documentation errors	Mental fatigue, reduced precision	Increase as the shift goes on longer
Missed monitor alarms	Habituation to stimuli, fatigue	More pronounced in the second half of the night shift

Type of error / adverse event	Mechanism of occurrence	Frequency / risk
Errors in clinical judgement	Impaired decision-making	Risk increases further after midnight
Injuries to medical staff	Reduced motor coordination	More frequent with rotating shift schedules

4. PREVENTION AND MEASURES TO PROTECT NURSES' HEALTH

Once the health risks associated with night work have been recognised, attention must be directed towards measures that can effectively reduce their consequences and preserve the health of nurses and medical technicians. Protecting employees who work night shifts requires a coordinated approach at the individual, organisational, and legislative levels. Since individual measures alone are not sufficient, only a systematic and comprehensive approach can bring about lasting improvements in the working conditions and health outcomes of this particularly exposed group of healthcare workers.

Aligning the circadian rhythm and maintaining proper sleep hygiene play an important role in preserving sleep quality and reducing fatigue. Education about proper sleep habits, a balanced diet, and regular physical activity can contribute to better sleep quality in nurses working night shifts [5]. Controlled exposure to light is also cited as one of the more effective methods of adjusting the circadian rhythm [6]. At the same time, the need for an individualised approach is emphasised, given that the working capacity of healthcare workers depends on age, work experience, family circumstances, and individual differences in the sleep–wake rhythm [8].

Proper organisation of shift work also plays an important role in protecting employees' health, although its implementation in practice is often hampered by a shortage of healthcare staff. Ergonomic shift schedules — which include rotation in the morning–afternoon–night direction, ensuring sufficient time for rest between shifts, and limiting the number of consecutive night shifts — can significantly reduce the physical and psychological strain of shift work [13]. The importance of rest between shifts is also recognised in the legislative framework. Directive 2003/88/EC of the European Parliament and of the Council stipulates workers' right to at least eleven hours of rest between two shifts [14], while the Labour Act of the Republic of Croatia establishes the right to at least twelve hours of uninterrupted daily rest within each 24-hour period [3]. Despite these legal provisions, owing to a chronic shortage of staff, healthcare institutions are often unable to fully ensure the prescribed rest conditions, which further increases the health risk for those who work at night.

Recommendations for reducing the negative consequences of night work also include limiting shift duration to a maximum of twelve hours, providing space for rest during work, and creating a working environment in which healthcare workers can report fatigue without fear of sanctions [15]. Particular emphasis is placed on the importance of systematically monitoring the health status of employees who work night shifts, as well as on the potential use of wearable devices to monitor alertness and identify a decline in cognitive performance in a timely manner [15].

Current scientific knowledge points to the need for further alignment of existing regulations with the proven health risks of night work. Although the legislative framework in the Republic of Croatia provides basic protection for workers employed on night shifts, healthcare institutions should develop comprehensive health protection programmes that include preventive health examinations,

psychosocial support, and individualised health risk assessment. Institutions that carry out regular preventive examinations, educational programmes, and systematic psychosocial support record lower rates of absenteeism, fewer errors, and greater satisfaction among medical staff [5].

5. CONCLUSION

Protecting the health of nurses and medical technicians who work night shifts is neither a privilege nor a cost; it is an investment in the entire healthcare system. A rested, healthy, and well-educated nurse provides better care, makes fewer errors, and remains in the profession longer. For precisely this reason, every healthcare institution should assume responsibility for the conditions in which its employees work, and health policymakers should provide the legal and organisational framework that supports this responsibility. It is therefore important to investigate the effects of night work on nurses and medical technicians in order to better understand the challenges they face and to develop measures to preserve their health, job satisfaction, and the quality of the care they provide to patients.

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Professional paper

VOLATILE ORGANIC COMPOUNDS IN THE AUTOMOTIVE INDUSTRY: SOURCES OF EMISSIONS AND IMPACT ON WORKERS' HEALTH

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Abstract: *The automotive industry, as one of the leading branches of modern industry, contributes significantly to air pollution with various chemical compounds, of which volatile organic compounds (VOCs) are particularly prominent. Due to their ability to evaporate at room temperature, as well as their chemical properties, volatile organic compounds can negatively affect the quality of air in workplaces and represent a potential health risk for workers. Exposure to VOCs can cause acute symptoms such as irritation and headaches, but also long-term health problems such as organ damage and an increased risk of cancer. Sources of volatile organic compounds in the automotive industry include painting, surface treatment, plastic processing, and cleaning and degreasing of metal parts, which cause volatile organic compounds to evaporate and quickly enter the working environment. Therefore, understanding the sources of VOCs and their impact on worker health is of great importance for improving occupational safety and reducing industrial air pollution. The aim of this paper is to provide an overview of the main sources of VOCs in the automotive industry and to analyze their potential impact on worker health and the working environment based on available scientific research and professional literature.*

Keywords: *volatile organic compounds (VOCs), automotive industry, occupational exposure, workers' health, occupational safety.*

1. INTRODUCTION

The automotive industry is one of the most important industrial sectors in the world, playing a key role in economic development, employment and technological innovation. However, the production of motor vehicles is associated with various environmental challenges, among which emissions of volatile organic compounds (VOCs) occupy a significant place. These compounds are formed during numerous production processes, including painting, degreasing, cleaning surfaces, the use of solvents and the processing of various materials and vehicle components. Volatile organic compounds are a group of organic chemicals that easily evaporate under normal atmospheric conditions. Their release into the environment can have negative consequences on air quality, human health and ecosystems. In addition to contributing to the formation of ground-level ozone

and photochemical smog, certain VOCs can be toxic, carcinogenic or cause various respiratory and neurological disorders in humans [1]. Given the increasingly strict environmental regulations and growing awareness of sustainable development, car manufacturers are investing significant efforts to reduce emissions of volatile organic compounds. The development of new painting technologies, the application of water-based coatings, the use of more environmentally friendly materials and the implementation of waste gas purification systems are some of the measures that aim to reduce the impact of vehicle production on the environment [2].

The aim of the paper is to analyze the sources of volatile organic compounds in the automotive industry, their impact on workers' health, and to present modern methods for their reduction and control. Through a review of the available literature and relevant research, an attempt will be made to provide a comprehensive overview of the issue and to point out the possibilities for further development of more sustainable production processes in the automotive industry.

2. DEFINITION AND CLASSIFICATION OF VOLATILE ORGANIC COMPOUNDS

In accordance with Directive 2004/42/EC of the European Parliament on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes and vehicle refinishing products, a Volatile Organic Compound (VOC) is defined as any organic compound having an initial boiling point of ≤ 250°C measured at a standard atmospheric pressure of 101.3 kPa [3]. Therefore, they evaporate at room temperature and normal pressure and can be present in both closed and open spaces. VOCs can be of natural or anthropogenic origin. Natural sources include vegetation, forest ecosystems and certain microorganisms, while anthropogenic sources are mainly associated with industrial processes, transportation, energy and the use of various chemical products. In industrial plants, VOCs are often used as solvents, cleaning agents, components of coatings, adhesives, and fuels. The World Health Organization (WHO), classifies the indoor organic contaminants as follows: organic compounds that are extremely volatile (VVOCs: methyl chloride, propane and butane); organic compounds that are volatile (VOCs: hexanal, formaldehyde, ethyl alcohol, d-Limonene, isopropyl alcohol, toluene, and acetone), and organic compounds that are semi-volatile (SVOCs: certain phthalates and flame retardants) [4].

Among the VOCs, three aromatic hydrocarbons known as BTX (benzene, toluene and xylene) stand out, which are often found in the environment, especially in the air. Gasoline contains an average of 1.8% benzene, 12.3% toluene, 1.6% ethylbenzene and 5.2% xylene. Therefore, automobile exhaust is a significant source of BTX exposure in the environment, that is, workers who may be in contact include areas such as testing stations, workshops and closed spaces.

Benzene (C_6H_6) is the simplest aromatic hydrocarbon compound. At room temperature, it is a colorless, highly volatile, flammable and toxic liquid with a strong, characteristic odor. It evaporates very quickly and is poorly soluble in water. Benzene is a natural component of crude oil (it makes up 1-5% of its volume) and is produced in large quantities in the petrochemical industry. Also, a significant source of benzene in indoor spaces is cigarette smoking. In addition, elevated concentrations of benzene have carcinogenic and genotoxic effects on the human body. Benzene is used in the chemical industry as a solvent (for fats and oils, resins, paints, etc.), and in the production of medicines, paints, varnishes, plastics, explosives, detergents and pesticides. Although benzene is increasingly avoided in industry due to its toxicity and carcinogenicity, it is still used in

some industrial processes. In certain cases, benzene is replaced by less harmful derivatives such as toluene or xylene.

Toluene ($C_6H_5CH_3$) is a non-corrosive liquid with a characteristic odor that evaporates easily. Its world production is estimated at 10 million tons. Most of the toluene produced is obtained in the process of increasing the octane value of gasoline, together with benzene and xylene. It is used in various industries, including the production of paints, adhesives and cosmetics. With other air pollutants, toluene contributes to smog. High concentrations of toluene can cause acute and chronic health problems, primarily related to the central nervous system [4,5].

Xylene ($C_6H_4(CH_3)_2$) is a colorless liquid with a sweet odor. In its liquid state, xylene is a volatile and flammable liquid that is insoluble in water but soluble in organic solvents. There are three isomeric forms of xylene: ortho-xylene (1,2-dimethylbenzene), meta-xylene (1,3-dimethylbenzene), and para-xylene (1,4-dimethylbenzene). It is obtained from petroleum and occurs naturally in kerosene, tar, and during forest fires. It is most commonly used as a solvent in the production of rubber and leather, but also as a cleaning agent and paint thinner. High concentrations of xylene can cause various neurological problems, such as headaches and reduced muscle coordination [5].

3. SOURCES OF VOLATILE ORGANIC COMPOUNDS IN THE AUTOMOTIVE INDUSTRY

In the automotive industry, volatile organic compounds are present during almost all stages of the production process. Main sources of VOCs in automotive industry are [6,7]:

- *Paint shops* – the largest source of emissions (50–70% of total VOCs), due to the evaporation of solvents from paints, varnishes and during drying.
- *Degreasing and cleaning of surfaces* – before painting the bodywork, it is necessary to remove oils, grease, dust and residual protective coatings. This is done using agents such as acetone, isopropanol, ethanol, methanol and hydrocarbon solvents.
- *Adhesives and sealants* – release various organic compounds during application and curing. Modern vehicles use tens of kilograms of adhesives and sealants. They are used to glue windows, attach trim, assemble bodywork, and as soundproofing. Adhesives can contain, for example, toluene, xylene, ethyl acetate, acetone, and styrene.
- *Plastic and composite part production* – emissions occur during the shaping and processing of materials. During production, injection molding, thermoforming, and composite manufacturing, styrene, formaldehyde, acrylates and other organic compounds may be emitted.
- *Rubber processes* – vulcanization and processing of rubber can emit VOC compounds. The production of rubber parts includes: seals, hoses, anti-vibration elements. During vulcanization, aromatic hydrocarbons, aldehydes, ketones, and organic sulfur compounds may be produced.
- *Printing and marking of parts* – solvents in printing inks often contain ethanol, isopropanol, ethyl acetate. Evaporation occurs immediately after application.

- *Vehicle interior materials* – plastics, foams, textiles and leather emit VOCs, especially in new vehicles. For example, polyurethane foams are used for seats, backrests and soundproofing, and can emit toluene, aldehydes and various amines.
- *Chemical storage* – evaporation from paint, solvent and thinner containers. Emissions in storage facilities occur due to the opening of containers, decanting, spilling and leaking.
- *Car repair shops and workshops* – VOCs are produced during vehicle painting, parts cleaning, degreasing, and body repairs. Common VOC compounds include acetone, toluene, xylene, and isopropanol.

Some common VOCs that appear in the automotive industry are shown in Table 1.

Table 1: Volatile organic compounds (VOCs) common in the automotive industry [6].

VOC	Boiling point (°C)	Use in the automotive industry
Toluene, C_7H_8	110.6	Often used as a solvent in paints, varnishes and adhesives
Xylene, C_8H_{10}	137-140	A component of thinners and coatings, used to improve the properties of paints
Benzene, C_6H_6	80.1	Present in fuels and certain industrial processes.
Ethylbenzene, C_8H_{10}	136.2	Used as a solvent and often occurs together with xylene
Acetone, C_3H_6O	56.1	Widely used for cleaning and degreasing surfaces
Methyl ethyl ketone, C_4H_8O	79.6	Used in the production of coatings and adhesives
Styrene, C_8H_8	145	Present in the production of plastic and composite vehicle parts
Isopropanol, C_3H_8O	82.5	Used for cleaning and preparing surfaces.
n-Hexane, C_6H_{14}	68.7	A component of certain solvents and degreasers.

4. IMPACT ON WORKERS' HEALTH

In the automotive industry, workers are often exposed to higher concentrations of VOCs than the general population, which can increase the risk of developing health problems. Occupational exposure to VOCs represents a significant health risk for workers, primarily through inhalation and skin contact. Short-term exposure can cause symptoms such as eye, nose, and throat irritation, headaches, dizziness, fatigue, and skin disorders. Long-term exposure has been associated with respiratory diseases, neurological impairments, liver and kidney damage, reproductive effects, and an increased risk of certain cancers. However, it is important to emphasize that such individual effects are substance and dose specific. Workers in paint shops, coating operations, and maintenance activities are particularly vulnerable due to higher concentrations of airborne VOCs. The severity of health effects depends on factors such as exposure duration, concentration levels, workplace ventilation, and the use of personal protective equipment [2,4].

The toxic effects of BTEX compounds have not been studied equally for all compounds. The most data have been collected for benzene, due to its hematotoxicity, followed by toluene, due to its neurotoxicity, while data on ethylbenzene and xylene are scarce. In general, organic solvents act locally on the skin and mucous membranes, and after absorption, systemic effects manifest themselves in the central nervous system. Neurotoxic effects can include headaches, dizziness, drowsiness, and in some cases, loss of consciousness. Due to its proven carcinogenicity, benzene

is classified as a human carcinogen. The neurotoxic effects of toluene are attributed to its effects on nerve cell membranes and myelin, which disrupts the transmission of nerve impulses. More severe neurological symptoms often occur in workers exposed to solvent mixtures, probably due to the synergistic effects of different compounds. Although ethylbenzene is generally considered less toxic than benzene and toluene, there is evidence of its adverse effects on the central nervous system [1,4,8].

5. TECHNOLOGIES AND MEASURES FOR REDUCING VOCs

VOC emissions contribute to air pollution, occupational health risks, and environmental degradation. To address these challenges, the industry has adopted various technologies and control measures aimed at reducing VOC emissions at the source and during production processes. Key strategies include the use of water-based and high-solid coatings, powder coating technologies, solvent substitution, advanced ventilation systems and emission control technologies such as thermal oxidizers, catalytic oxidizers, adsorption systems and biofiltration. In addition, process optimization, automation, regular maintenance and employee training play important roles in minimizing VOC release. The implementation of these technologies not only helps industries comply with environmental regulations but also improves workplace safety, reduces operational costs, and supports sustainable manufacturing practices [6,9].

Process and engineering controls are among the most effective strategies for reducing VOC emissions in the automotive industry. These controls focus on minimizing VOC generation at the source, improving production efficiency, and preventing worker exposure to harmful airborne contaminants. Technologies such as automated paint application systems, enclosed spray booths, local exhaust ventilation, and optimized manufacturing processes significantly reduce solvent consumption. Engineering controls help capture and remove contaminants before they disperse into the workplace environment, thereby enhancing air quality and protecting worker health. Moreover, technologies such as UV-curable coatings, waterborne coating systems, powder coatings, robotic paint application, and smart VOC monitoring systems significantly lower VOC emissions compared to conventional methods [9].

6. CONCLUSION

Volatile organic compounds (VOCs) represent one of the most significant environmental and occupational health challenges associated with automotive manufacturing. Throughout the vehicle production process, VOCs are generated from numerous sources, including paint shops, surface cleaning and degreasing operations, adhesives and sealants, plastic and composite manufacturing, rubber processing and vehicle repair activities. Workers in the automotive industry are particularly vulnerable to VOC exposure due to their direct involvement in production processes. Both short-term and long-term exposure can result in adverse health effects ranging from irritation and headaches to respiratory diseases, neurological disorders, organ damage and an increased risk of certain cancers. Therefore, effective occupational safety measures, exposure monitoring and proper ventilation systems are essential for protecting worker health. To address these concerns, the automotive industry has increasingly adopted advanced technologies and control measures aimed at reducing VOC emissions. The use of water-based and powder coatings, low-VOC materials, automated painting systems, local exhaust ventilation, thermal oxidation technologies and real-time monitoring

systems has significantly improved environmental performance and workplace safety. Furthermore, emerging sustainable technologies, including UV-curable coatings, robotic applications, and green chemistry solutions, offer promising opportunities for further emission reductions.

Reducing VOC emissions requires a comprehensive approach that combines technological innovation, engineering controls, regulatory compliance and sustainable manufacturing practices. Continued research and development of environmentally friendly materials and production processes will play a crucial role in minimizing the environmental footprint of the automotive industry while ensuring safer working conditions and supporting long-term sustainable development.

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Review article

PSYCHOSOCIAL RISKS AND QUALITY OF LIFE AMONG NURSES: EVIDENCE FROM A PORTUGUESE HOSPITAL

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Abstract: *This study analyses psychosocial risks and their influence on the quality of life of nurses in a Portuguese hospital. It highlights the impact of working conditions on the physical, mental and social health of these professionals, associated with factors such as high workload, emotional demands and organisational challenges. The research followed a descriptive and correlational methodology and used the COPSOQ II and WHOQOL-Bref instruments to assess psychosocial risks and quality of life of nurses. The sample consisted of 95 nurses from a hospital in Alentejo, within a total population of 447 nurses. The aim was to identify critical factors and propose preventive strategies and improvements in management. The dissertation results showed that higher exposure to psychosocial risks was associated with a lower perception of quality of life, particularly in the physical and psychological domains; workload, limited autonomy, lack of professional recognition and reduced social support emerged as the most impactful factors. These findings support the need for targeted occupational health strategies, including the SelfCare intervention programme proposed in the dissertation.*

Keywords: *Nurses, Quality of Life, Psychosocial Risks*

1. INTRODUCTION

The inherent characteristics of the nursing profession may lead to some confusion between Psychosocial Risks (PR) (excessive workload, challenging tasks, flexible schedules, lack of entitlement to holidays or weekends off, etc.) and the demands of the job, where nurses, in their constant pursuit of excellence in professional practice, carry out their activities in an autonomous and

altruistic manner, but with the same "excessive workload and stimulating and challenging tasks" [1]. In this way, it can be concluded that although working hours and workload intensity may be similar, a positive or favourable psychosocial environment can contribute to good performance, personal development, and the physical and mental well-being of workers.

Psychosocial risks related to work activity have gradually gained significant prominence in the field of Occupational Safety and Health (OSH) due to the substantial impact they may have on people's health, on organisations, and even on the social and economic context of a given country. Therefore, it is essential to act in terms of prevention, monitoring, treatment, rehabilitation, and support for workers who may develop conditions associated with these risks [2].

In view of the above, we decided to study the Influence of Psychosocial Risks on the Quality of Life (QoL) of Nurses in a Hospital in the south of Portugal.

2. LITERATURE REVIEW

When examining the etymological meaning of the word *"work"*, its origin in the Latin term *tripalium* appears associated with an instrument of torture commonly used in the European region. However, today work is regarded not only as an important means of subsistence, but also as an activity that provides social recognition and personal fulfilment. On the other hand, globalization, technological advances, and the high level of business competitiveness, often accompanied by precarious employment contracts and job instability, have brought about significant changes in the world of work. These changes have had important consequences for the organization of work methods, as well as for the rights and duties of both workers and employers [2; 3]. Concurrently, the COVID-19 pandemic also triggered a series of profound labour-related changes that exacerbated the psychosocial risks to which health professionals, and particularly nurses, are exposed in the workplace [2].

The etymological origin of the term *"health"* derives from the Latin *salus* (wholeness) and the Greek *holos* (totality), reflecting the complexity and breadth of the concept, which throughout history has been influenced by different cultural, scientific, and philosophical perspectives [4]. In 1948, several countries joined together to establish the World Health Organization (WHO), which defined *health* as a state of complete physical, social, and mental well-being, and not merely the absence of disease [4; 5; 6].

Although innovative, this WHO definition has been criticized for being abstract and idealistic, for neglecting emotional, spiritual, and contextual aspects, and for suggesting a static state rather than a dynamic process [4]. Consequently, the concept of health has evolved towards a holistic approach, integrating biological, social, political, and economic dimensions, with the aim of achieving a more comprehensive and functional definition [4]. Within this framework, social determinants directly influence workers' QoL and, consequently, their health.

2.1. Psychosocial Risks

Mental disorders and psychosocial problems represent a significant global health challenge. According to the World Health Organization, approximately 450 million people were affected by mental health conditions, with depression predicted to become one of the leading causes of disease worldwide [5]. In contemporary societies, increasing professional demands, combined with social

expectations of high performance and constant achievement, may lead workers to exceed their physical, social and psychological limits [7]. In this context, healthcare institutions represent particularly demanding work environments due to their complex organisational structures and continuous transformation.

The International Labour Organization highlights the importance of studying anxiety, stress and depression in the workplace in order to identify their causes and develop preventive policies that promote workers' health [5]. Psychosocial risks associated with occupational activity have therefore gained increasing relevance in the field of Occupational Safety and Health (OSH) due to their significant impact on workers' health, organisational performance and national economies [2;8;9].

Psychosocial risks are generally understood as the interaction between the work environment, organisational conditions and individual characteristics that may influence workers' health, performance and job satisfaction [10]. They may arise from inadequate work design, organisation or management, as well as from demanding work environments that generate psychological, physical and social consequences [1]. From an occupational risk assessment perspective, psychosocial risks result from the interaction between the probability of harmful exposure and the severity of its potential effects on workers' physical, mental and social health [2].

Research indicates that psychosocial risks originate from multiple organisational, managerial and individual factors. These include aspects related to workload, work organisation and working time, socio-relational dynamics in the workplace, and the balance between professional, family and social life [2]. When work demands exceed workers' capacity to respond, stress may arise, potentially leading to both physical health problems, such as cardiovascular diseases, gastric ulcers and musculoskeletal disorders, and mental health problems, including burnout, anxiety and depression [1].

The consequences of psychosocial risks extend beyond individual health, affecting behaviour, work performance and organisational functioning. Studies identify occupational stress as one of the most recognised psychosocial risks, although other important issues include burnout, workplace violence, harassment and bullying [3;8;11;13;14]. In addition, psychosocial risks may result in various physical symptoms such as insomnia, headaches, hypertension, musculoskeletal disorders and chronic fatigue [2;3;8].

At the behavioural and organisational level, these risks may lead to absenteeism, presenteeism, interpersonal conflicts, increased staff turnover, work errors and reduced productivity [8]. Such outcomes may negatively affect organisational reputation and performance, while also generating broader social impacts by affecting workers' personal and family relationships and increasing costs for social and health systems [1].

Within the healthcare sector, psychosocial risks are particularly relevant due to their potential impact on the quality and safety of patient care. The RN4CAST study highlighted the relationship between nurses' work environments, professional exhaustion and patient outcomes, demonstrating how organisational conditions and workload may influence both nurses' well-being and patient mortality [11;12]. Given these consequences, organisations should adopt preventive strategies aimed at promoting healthy work environments. Measures such as psychological support programmes, effective communication between management and staff, participatory decision-making and supportive leadership practices are essential for reducing psychosocial risks and improving workers' Quality of Life and organisational well-being.

2.2. Quality of Life

Quality of Life (QoL) is a widely used concept in the social and health sciences; however, it remains complex and sometimes ambiguous due to the subjective nature of its definition and measurement. As highlighted by Awad and Voruganti, QoL is often discussed but not always clearly defined, as it depends on individual perceptions influenced by sociocultural contexts, personal goals, expectations and concerns [15]. Consequently, QoL is generally understood as a multidimensional concept that integrates physical, psychological, social and spiritual dimensions, as well as the individual's interaction with their surrounding environment.

Schalock and Siperstein identified eight key components of QoL, emotional well-being, interpersonal relationships, material well-being, personal development, physical well-being, self-determination, social inclusion and rights, highlighting its multidimensional and hierarchical nature [16]. Within this framework, occupational activity and the psychosocial conditions of the work environment play a significant role in influencing individuals' overall quality of life.

Several instruments have been developed to measure QoL, including the WHOQOL-100, the SF-36 Health Survey and the Sickness Impact Profile. However, the lack of a consensual definition led the World Health Organization to promote new conceptual and methodological approaches aimed at improving the assessment of QoL and capturing its subjective dimension more accurately [5].

In the healthcare sector, psychosocial risks affect various professional groups, but nurses are particularly exposed due to the nature of their work. Continuous care provision, frequent contact with patients experiencing vulnerability and suffering, high emotional and cognitive demands, shift work and long working hours contribute significantly to this exposure. These factors may negatively influence nurses' QoL and mental health, increasing the risk of burnout and other psychosocial problems [17].

Empirical evidence supports the relationship between psychosocial risks and QoL. Studies indicate that organisational support, fair working conditions, workload management and access to psychological support are important strategies for promoting workers' well-being and improving their QoL. Research conducted by Gaspar et al. demonstrated a statistically significant relationship between psychosocial risks and QoL, reinforcing the importance of understanding health from a biopsychosocial perspective [18].

Similarly, a scoping review by Lima et al. identified numerous factors associated with poorer QoL among nurses, including burnout, stress, excessive workload, shift work, exposure to suffering, violence, difficulties in balancing personal and professional life and demanding work environments [13]. Conversely, education level, professional experience and training were identified as protective factors. These findings also suggest that occupational stress, lack of autonomy and limited professional recognition may negatively affect both nurses' QoL and the quality of care provided [13].

Furthermore, Farias et al. emphasised the importance of implementing organisational and individual strategies to prevent occupational stress and highlighted the need for further empirical research in Portugal in order to strengthen scientific evidence in the field of occupational health [9].

Given the complexity and relevance of these issues, it is essential to deepen the understanding of psychosocial risks and their influence on nurses' QoL. Developing empirical studies in hospital settings, particularly in the Alentejo region, may contribute to the implementation of preventive strategies within Occupational Safety and Health, ultimately improving nurses' health, well-being and quality of life.

3. METHODOLOGY

Psychosocial risks in the workplace have consequences that go beyond stress and burnout, affecting organisational functioning and influencing nurses' quality of life (QoL) in multiple dimensions. This study aims to analyse the influence of psychosocial risks on the QoL of nurses working in a hospital in the Alentejo region, Portugal.

A descriptive–correlational study design was adopted to explore the relationship between psychosocial risks and nurses' QoL. The study population consisted of nurses working in a hospital in southern Portugal, with a non-probabilistic convenience sample of 95 professionals, selected from a total population of 447 nurses, who had at least three years of experience and full-time employment.

Data were collected through a structured questionnaire composed of three sections: the COPSOQ II (short Portuguese version) to assess psychosocial risks, the WHOQOL-Bref to evaluate quality of life, and a questionnaire addressing sociodemographic and socioprofessional characteristics.

The study examines the prevalence of psychosocial risks, their relationship with sociodemographic and professional variables, and their association with nurses' QoL. The main hypothesis assumes that a higher perception of psychosocial risks is associated with lower levels of QoL among nurses.

Data were analysed using descriptive and inferential statistical methods with SPSS®, aiming to identify relationships between psychosocial risks and quality of life and to support the development of preventive strategies to improve occupational health and promote healthier work environments in hospital settings.

4. ANALYSIS AND DISCUSSION OF RESULTS

The empirical study included 95 nurses from a hospital in Alentejo, within a total population of 447 nurses. The results confirmed a negative correlation between psychosocial risks and all domains of perceived quality of life. Higher exposure to psychosocial risks was associated with lower QoL scores, with the physical and psychological domains presenting the lowest results. The most impactful psychosocial risk factors were work overload, lack of professional recognition, limited autonomy and insufficient social support. Sociodemographic and socioprofessional variables, including age, gender, length of service, contractual relationship and hospital service, also influenced nurses' perceptions. Based on these findings, the dissertation proposed the SelfCare programme as an occupational health intervention to prevent psychosocial risks and promote nurses' well-being.

Over recent decades, workplace anxiety, stress and depression have attracted increasing attention from the International Labour Organization, highlighting the need to implement policies and strategies aimed at promoting workers' health and social protection [7;10]. In this context, Occupational Safety and Health (OSH) should not focus solely on physical, biological, ergonomic and chemical risks, but must also address psychosocial risks in their different dimensions to ensure a holistic approach to workers' health.

Psychosocial risks are recognised as important determinants of workers' health, professional performance, job satisfaction and Quality of Life (QoL) [2]. Consequently, it is essential to understand their presence within professional contexts in order to develop strategies that prevent negative

effects on productivity and well-being while promoting healthy and sustainable work environments [8]. The European Agency for Safety and Health at Work also identifies psychosocial risks as one of the most significant challenges in the field of OSH due to their impact on individuals, organisations and national economies [1].

Within the healthcare sector, nurses are particularly exposed to psychosocial risks, which may compromise their physical and mental health if not adequately assessed and managed [8]. In this regard, protective factors such as recognition, social support, autonomy and participation in decision-making processes have been identified as important elements for promoting workers' mental health and well-being [2]. These conditions contribute not only to improved QoL but also to greater job satisfaction, motivation and productivity within organisations.

Portuguese legislation also reinforces the importance of preventing psychosocial risks. Law No. 102/2009 establishes the employer's responsibility to ensure that psychosocial risk factors do not compromise workers' safety and health and requires the adaptation of work conditions to workers' needs [22]. However, the effective implementation of these measures requires systematic risk assessment and continuous monitoring within organisational contexts [23].

Research highlights several strategies for the prevention of psychosocial risks among nurses, including adequate staffing levels, interdisciplinary communication, conflict management training, psychosocial support, recognition practices and the reorganisation of work schedules to facilitate work–life balance [8]. Such measures contribute to healthier work environments and play a crucial role in promoting workers' health, well-being and overall Quality of Life [2;8].

5. CONCLUSION

This study contributed to consolidating important knowledge regarding the assessment of psychosocial risks in the workplace, particularly in the context of the increasing demands and transformations observed in contemporary society and organisational environments. Professions characterised by high physical and emotional demands, such as Nursing, expose professionals to several risk factors, including rotating shifts, heavy workloads, and continuous contact with suffering, illness and death. These conditions may lead to increased levels of anxiety, stress and depression, highlighting the need for policies and strategies that promote workers' health and social protection within a holistic perspective [8].

Given that psychosocial risks directly affect workers' health, professional performance and job satisfaction, organisations must implement mechanisms for their effective management. Such measures are essential to ensure nurses' well-being, promote a better balance between professional and personal life, and ultimately improve both Quality of Life and organisational productivity.

The nursing work environment is characterised by significant cognitive and emotional demands, intense work rhythms and high levels of professional responsibility, often aggravated by staff shortages. These conditions make nurses a particularly relevant group for research and monitoring, since the pressures associated with their work may lead to errors or omissions with serious consequences for patient care.

In this context, the prevention and management of psychosocial risks should involve integrated organisational strategies, including periodic risk assessments, adequate staffing levels, interdisciplinary communication, training in conflict management, psychosocial support and recognition initiatives

that promote work–life balance [8]. Such measures not only enhance professionals' well-being and health but also contribute to increased job satisfaction, improved organisational performance and the development of healthier and more productive work environments.

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Review article

CHALLENGES OF EMERGENCY RECEPTION IN CONDITIONS OF INCREASED SYSTEM LOAD – MAJOR ACCIDENTS AND DISASTERS

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Abstract: *Major incidents are extraordinary events in which the number of injured or deceased exceeds the usual capacity of emergency services for initial care. They require rapid and specialized organization of the entire hospital system. The most common causes include traffic accidents, natural disasters, and industrial incidents. Timely activation of the emergency response system is essential. Triage is performed to determine treatment priorities with the aim of saving as many lives as possible while making optimal use of human and financial resources. Precise coordination between emergency medical services, firefighters, and the police is necessary, along with clear communication and a defined command structure in the field. Education and continuous training of personnel are of crucial importance for effective response, thereby reducing the risk of loss of control over the system*

Keywords: *emergency medical services, hospital surge capacity, mass casualty incident, triage*

1. INTRODUCTION

Major accidents and disasters represent one of the greatest challenges facing the modern healthcare system. The development of urban environments, increasing traffic, climate change, and technological progress contribute to a greater likelihood of events that can cause large numbers of

injured persons and seriously jeopardize the functioning of communities and healthcare institutions. In the Republic of Croatia, key roles in the response to major accidents are played by the Croatian Institute of Emergency Medicine, the Croatian Firefighting Association, the Ministry of the Interior, and the Civil Protection Directorate [1]. The success of the response to such events depends largely on their mutual cooperation, the timely exchange of information, and good coordination among all those involved in the intervention.

In major accident situations, the healthcare system faces a sudden increase in the number of patients requiring emergency care. Such events often exceed the usual capacities of the emergency medical service and of hospital emergency receptions, and they require rapid organizational adjustment. Timely recognition of the scale of the incident, the mobilization of human and material resources, and effective communication among services are essential for the successful care of injured persons [1].

Triage is of particular importance during major accidents — a procedure by which casualties are sorted according to the urgency of medical care so that the available resources are directed toward the patients most in need of help [2]. At the same time, hospital institutions switch to a crisis mode of operation that includes reorganizing the emergency reception, activating additional staff, increasing the capacity to admit patients, and adjusting the work of hospital departments [3].

Emergency reception staff, including nurses and medical technicians, play an important role in organizing admissions, in triage, in monitoring patients' conditions, and in coordinating further care. Emergency receptions are among the first parts of the healthcare system to feel the consequences of the increased load during major accidents and disasters.

The aim of this paper is to present the organization of the response to major accidents and disasters and the role of the emergency medical service and the hospital system, and to highlight the challenges faced by hospital emergency receptions under conditions of increased system load.

2. MAJOR ACCIDENTS AND DISASTERS

A major accident is a sudden event that causes a large number of injured or fatally injured persons and requires a special organizational response because of the disproportion between the need for care and the available resources [1, 2]. In such situations, the regular capacities of the emergency services and the healthcare system are often insufficient to effectively care for all casualties, which is why the rapid mobilization of additional human and material resources and coordinated action by all the services involved in the response to the accident are necessary.

Major accidents are characterized by a large number of casualties within a short period of time, the need for the urgent deployment of emergency and security services, possible threats to infrastructure, and difficult access to the scene [1]. Additional challenges include disruptions in communication, shortages of medical equipment and logistical support, and an increased load on the healthcare system. In such circumstances, triage and priority-care procedures are of particular importance, as they seek to ensure timely care for those with the most severe injuries and the optimal use of available resources.

2.1. Types of major accidents and disasters

Major accidents and disasters can be divided into several groups, depending on their cause and the specific features of the response they require [1, 2].

Natural disasters include earthquakes, floods, fires, storms, and landslides. Such events often cause significant damage to infrastructure, disrupt transport and communication links, and hinder access to casualties. Their consequences can be long-lasting and may require the extensive organization of rescue, evacuation, and remediation of the affected area.

Large-scale traffic accidents most often include bus accidents, multi-vehicle pile-ups on motorways, railway accidents, and aircraft accidents. They are characterized by a large number of injured persons within a short period of time, which is why rapid and effective coordination of the emergency medical service and of firefighting and police forces is essential.

Industrial and technological accidents include explosions, fires in industrial facilities, and the release of hazardous chemical or biological substances. In addition to the immediate danger to casualties, they can pose a serious risk to the population and the environment, and they require the implementation of special protection, rescue, and decontamination measures.

Epidemics and pandemics of infectious diseases represent a special form of major accident that can place a prolonged burden on the healthcare system. In such circumstances, it is necessary to adapt the organization of work in healthcare institutions, to provide additional capacity for the treatment and isolation of patients, and to implement epidemiological measures aimed at preventing the further spread of the disease.

Security threats, such as terrorist attacks and other violent incidents, pose a particular challenge because of the need for simultaneous action by medical, police, and security services. In addition to caring for the injured, it is necessary to secure the scene, protect those involved in the intervention, and prevent the emergence of further threats to public safety.

2.2. Organization of the response to a major accident

Action in major accidents is based on predefined protocols, crisis plans, and the coordinated action of the various emergency services. The goal of an organized response is the timely saving of lives, the reduction of the consequences of the accident, and the efficient use of available human and material resources [1, 4].

The response to a major accident begins with the receipt of the alert and an initial assessment of the event. Upon the arrival of the first services at the scene, an assessment is made of the number of casualties, the safety of the scene, the possibility of further hazards arising, and the need to deploy additional teams, equipment, and other resources. A timely and accurate assessment of the situation is the basis for the further organization of the intervention.

In the early phase of the intervention, a chain of command is established that defines responsibilities, the manner of communication, and the coordination of all services involved in the response to the accident. The incident commander coordinates activities at the scene and makes decisions on the priorities of action in accordance with the assessment of the situation.

Important elements of the organization of the response include securing the scene in order to protect casualties and members of the emergency services, rescuing and evacuating people from

the endangered area, and carrying out triage to determine care priorities according to the severity of injuries [1, 2]. At the same time, emergency medical care is provided at the scene, and the transport of patients to appropriate healthcare institutions is organized.

It is particularly important to prepare the hospital emergency reception in good time for the admission of a larger number of patients. This includes activating crisis plans, mobilizing additional staff, preparing space and equipment, and coordinating between the emergency medical service and hospital teams in order to ensure the uninterrupted care of casualties.

In addition to medical activities, an important role is played by logistical support, the provision of communication systems and the necessary equipment, and the provision of psychological assistance to casualties, members of their families, and those involved in the intervention. A well-organized and coordinated response significantly contributes to reducing mortality, complications, and the permanent consequences of injuries, and enables the healthcare system to function more effectively during crisis situations.

2.3. Challenges during the response to a major accident

During the response to major accidents, numerous challenges may arise that hinder the effective operation of the emergency services and the healthcare system. The complexity of such situations requires rapid adaptation, good organization, and coordinated action by all participants in the intervention. One of the most common problems is a shortage of staff, especially in situations where the number of casualties significantly exceeds the available capacities. In addition to human resources, shortages often arise in medical equipment, medicines, vehicles, and other material resources needed for the effective care of casualties.

The increased influx of patients during major accidents places an additional burden on the emergency medical service and on hospital emergency receptions. In such circumstances, delays may occur in the processing and care of patients, there may be a lack of space to admit a larger number of casualties, and coordination between the emergency reception, diagnostic services, and hospital departments may become difficult.

A further challenge is difficult access to the scene due to damaged infrastructure, traffic congestion, debris, or unfavorable weather conditions. In such circumstances, the arrival of rescue teams and the transport of casualties may be considerably slowed, which can have a negative effect on the timeliness of the provision of healthcare.

During major accidents, communication systems are often disrupted or overloaded, which hampers coordination among services and the timely exchange of information. A lack of reliable communication can slow down decision-making and adversely affect the organization of the intervention.

Major accidents also cause significant emotional stress for casualties, members of their families, and members of the emergency and rescue services as well. Panic, fear, and psychological pressure can further hinder the conduct of rescue and medical care. A particular challenge is the possibility of secondary accidents occurring, which can endanger the safety of rescue teams and further increase the number of casualties. For this reason, the safety of the scene is one of the most important priorities throughout the entire intervention.

The continuous education of healthcare and rescue personnel, investment in modern equipment, and the regular conduct of simulation exercises are essential for strengthening the readiness of the system and for more effective action in major accident situations [1, 5].

3. THE ROLE OF EMERGENCY MEDICAL SERVICES

The emergency medical service plays a key role in the response to major accidents and disasters. Emergency medical service teams are most often the first to arrive at the scene and begin organized medical action with the aim of saving lives and reducing the consequences of injuries.

Upon arrival at the scene, an initial assessment of the situation is carried out, which includes assessing the safety of the scene, the number of casualties, and the severity of their injuries. On the basis of the information gathered, the further course of the intervention is planned, and care priorities and the need for additional forces and resources are determined.

One of the most important tasks of the emergency medical service is performing triage, that is, sorting casualties according to the urgency of medical care. Triage ensures that persons with life-threatening injuries receive priority medical care, and it is one of the key procedures in conditions involving a large number of casualties [1, 2 ,5].

Physicians, nurses, medical technicians, and other members of the emergency medical service teams carry out measures to maintain vital functions, including securing the airway, controlling bleeding, immobilizing injuries, and other emergency medical procedures at the scene [5, 6]. The goal is to stabilize the patients' condition and prepare them for safe transport to an appropriate healthcare institution.

An important part of the work of the emergency medical service is organizing the transport of casualties to hospitals, depending on the severity of injuries and the available capacities of healthcare institutions [7]. The timely distribution of patients among hospitals is particularly important during major accidents in order to prevent the overloading of individual emergency receptions and to enable the effective care of all casualties.

Throughout the entire process, continuous communication with hospitals and other emergency services is necessary in order to ensure effective coordination and the timely transfer of information. In major accident situations, the emergency medical service is one of the most important elements of the protection and rescue system, and its rapid, professional, and organized response significantly affects the reduction of mortality and of the consequences of injuries.

3.1. Triage under major accident conditions

Triage is one of the most important procedures during the response to a major accident. Its purpose is to quickly identify patients who require urgent medical care and to ensure the optimal use of available resources. In situations where the number of casualties exceeds the capacity for immediate care, triage makes it possible to determine the priorities for treatment and transport [1, 2].

During major accidents, the START (Simple Triage and Rapid Treatment) triage system is most commonly used, by which patients are sorted according to the urgency of care:

- red category – immediately life-threatened patients who require urgent medical intervention,
- yellow category – severely injured patients whose condition requires medical care but who are not in immediate life-threatening danger,
- green category – lightly injured patients who can wait for care,
- black category – deceased persons or persons with injuries incompatible with life.

The goal of triage is to make it possible to save as many lives as possible while making rational and efficient use of the available human and material resources [1, 2].

4. HOSPITAL RESPONSE TO INCREASED SYSTEM LOAD

Hospitals play a key role in caring for a large number of patients during major accidents and disasters. In such situations, there is a sudden increase in the need for emergency medical care, which can significantly burden the existing capacities of the healthcare system. In order to ensure the effective functioning of a hospital during crisis events, every healthcare institution must have a prepared crisis response plan and defined levels of mobilization [2].

The activation of a particular level of mobilization depends on the number of casualties, the severity of their injuries, the assessment of how events are developing, and the available hospital capacities. The goal of mobilization is to ensure the timely care of patients, to maintain continuity of healthcare, and to enable the efficient use of available resources.

4.1. Levels of hospital mobilization

First level of mobilization is activated when there is a minor increase in the number of patients and the existing capacities still allow the hospital to function normally. In this phase, the operation of the emergency reception is usually intensified, additional healthcare staff are called in, operating rooms are prepared, and additional patient beds are provided for the admission of patients.

Second level of mobilization is activated when the number of casualties significantly burdens the hospital system. At that point, elective procedures are postponed, healthcare personnel are reassigned, the crisis management team is activated, and the capacity of intensive care units and other key hospital services is increased.

Third level of mobilization is applied during catastrophic events with a large number of victims and an extreme burden on the healthcare system. In such circumstances, there is a complete reorganization of the hospital's operations, the activation of all available human and material resources, the involvement of other healthcare institutions, and the organization of additional or temporary spaces for the care of patients.

Regardless of the level of mobilization, one of the most important goals of the hospital response is to ensure the uninterrupted operation of the emergency reception and the timely care of all patients. Under conditions of increased system load, hospitals switch to a crisis mode of operation with the aim of ensuring the timely care of patients, saving as many lives as possible, and reducing the consequences of major accidents and disasters.

5. COMMUNICATION AND COORDINATION OF EMERGENCY SERVICES

Effective communication and coordination among the emergency services are among the key prerequisites for a successful response to a major accident. In situations involving a large number of casualties, the timely exchange of information makes it possible to make rapid, high-quality decisions and to use the available resources effectively. A lack of coordination or a delay in the transfer of information can lead to difficulties in caring for patients, to a prolongation of the intervention time, and to an increase in the number of victims [8].

Communication between the emergency medical service, firefighting and police forces, civil protection, and healthcare institutions must be clear, timely, harmonized, and organized. It is particularly important to ensure the continuous transfer of information about the number of casualties, their medical condition, the need for additional resources, and the available hospital capacities.

Modern systems for responding to major accidents use various communication tools and technologies, including digital communication systems, centralized operations centers, GPS systems, and hospital information systems. Their use enables better coordination of activities at the scene, more efficient resource management, and improved connectivity between field teams and hospital institutions.

Regular simulation exercises and joint training of the emergency services play an important role in improving communication and mutual cooperation. Such activities make it possible to identify potential weaknesses in the system, improve the readiness of personnel for crisis situations, and reduce the possibility of errors occurring during actual interventions [1, 6, 2].

6. CHALLENGES OF HOSPITAL EMERGENCY RECEPTION DURING MAJOR ACCIDENTS

Major accidents pose a significant challenge for hospital emergency receptions because of the sudden influx of a large number of injured persons within a short period of time. Such situations can lead to the overloading of the emergency reception, operating rooms, intensive care units, and hospital departments, and can jeopardize the timeliness of the provision of healthcare. The most common challenges include staff shortages, limited spatial capacity, shortages of medical equipment, and difficulties in organizing work [2].

A particular challenge is the conduct of triage, which makes it possible to determine treatment priorities and to use the available resources rationally. At the same time, the increased number of patients and the heightened workload of healthcare personnel can increase the risk of errors and hinder the effective functioning of the emergency reception [1, 2].

Additional difficulties are associated with the availability of medicines, blood, medical equipment, and protective equipment, which is why it is necessary to plan supply systems in advance and to maintain appropriate reserves of key resources [2].

The successful functioning of the hospital emergency reception during major accidents depends on the timely organization of resources, effective triage, the availability of healthcare staff, and the

continuous education and preparedness of healthcare personnel. Regular simulation exercises and the development of crisis plans contribute to a more effective response by the healthcare system and to a reduction in the consequences of major accidents [1,2].

7. CONCLUSION

Major accidents and disasters pose a serious challenge for the healthcare, security, and organizational systems because of the large number of casualties, the limited resources, and the need for rapid decision-making. A successful response to such events requires effective organization, the timely mobilization of resources, and coordinated action by the emergency medical service, hospitals, and other emergency services.

Triage, effective communication, and the adaptation of the healthcare system to conditions of increased load are of particular importance. Hospital emergency receptions are among the first to face the consequences of major accidents, which is why their organizational readiness significantly affects the quality of patient care and treatment outcomes.

The continuous education of healthcare personnel, regular simulation exercises, the development of crisis plans, and investment in equipment are essential for strengthening the resilience of the healthcare system. Only a well-organized and coordinated system can ensure the timely and high-quality care of casualties and respond effectively to the challenges of major accidents and disasters.

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Professional paper

ASSESSMENT OF INDOOR AIR QUALITY IN EDUCATIONAL INSTITUTIONS BASED ON AIRBORNE PARTICLE NUMBER CONCENTRATIONS

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Abstract: *Indoor air quality is an important factor affecting health, well-being, and performance in educational environments with high occupancy levels. Airborne particulate matter is a key indicator of indoor pollution and may have adverse effects on the respiratory system. Fine particulate matter (PM2.5) can penetrate deep into the lungs and may pose risks to human health. This study assesses airborne particle number concentrations in selected university spaces under real-use conditions. Measurements were conducted before and after educational activities using a portable particle counter, focusing on particle size fractions corresponding to PM2.5 and PM10, together with temperature and relative humidity. PM2.5 particle number concentrations varied among the monitored spaces, with changes after occupancy differing according to room characteristics and ventilation practices. Most locations showed an increase after educational activities, whereas one lecture room showed a decrease following window ventilation. Because particle number concentrations (pcs/L) cannot be directly compared with mass-based guideline values (μg/m³), the results are interpreted comparatively across the monitored spaces and in relation to recent studies on occupancy and ventilation in educational buildings. The findings provide evidence supporting more extensive and continuous monitoring of indoor air quality in university environments.*

Keywords: *indoor air quality, educational environments, airborne particles, particle number concentration, PM2.5 / PM10*

1. INTRODUCTION

Indoor air quality is an important factor affecting human health, well-being, and performance in indoor environments [1]. Educational institutions represent a specific type of indoor environment characterized by high occupancy levels and prolonged periods of stay, making adequate air quality particularly important [2,7]. Among the various indicators of indoor air quality, airborne particulate

matter is considered one of the most relevant due to its potential impact on human health [1]. Airborne particles are commonly classified according to their aerodynamic diameter. PM2.5 refers to particles with diameters smaller than 2.5 μm, while PM10 refers to particles with diameters smaller than 10 μm. Fine particles can remain suspended in the air for extended periods and may penetrate deep into the respiratory system, potentially contributing to respiratory and cardiovascular diseases [1,3]. Particle concentrations in indoor environments are influenced by several factors, including occupancy, ventilation conditions, indoor activities, and outdoor pollution sources [2,4,6]. Sources of indoor particles may include human activity, resuspension of settled dust, cleaning activities, and infiltration of outdoor air. Previous studies have highlighted the importance of monitoring indoor air quality in educational buildings, where occupancy and ventilation conditions can significantly influence airborne particle concentrations [2,4,6,7]. The importance of monitoring airborne particles is also reflected in international guidelines and standards. The World Health Organization (WHO) has identified particulate matter as one of the most significant environmental health risks and established guideline values for PM2.5 and PM10 concentrations [1]. In educational buildings, indoor environmental quality is commonly addressed through ventilation and comfort standards. European Standard EN 16798-1 provides recommendations for indoor environmental quality and ventilation in non-residential buildings, including educational facilities [5]. Educational buildings represent a unique category of indoor environments due to the diversity of activities and occupancy patterns occurring throughout the day. Lecture rooms, libraries, laboratories, and administrative offices differ considerably in terms of occupant density, ventilation practices, and indoor environmental conditions. As a result, indoor air quality may vary significantly among different spaces within the same institution. Monitoring airborne particles in university buildings can provide valuable information for facility management and support decision-making related to ventilation strategies and indoor environmental quality [6,7]. Such measurements can contribute to a better understanding of factors affecting the exposure of students and staff to airborne pollutants and help identify opportunities for improving indoor environmental conditions. This paper presents an assessment of indoor air quality in selected university facilities, including lecture rooms, a library, a laboratory, an administrative office and a large hall. Measurements were conducted before and after educational activities using a portable particle counter to determine particle number concentrations (pcs/L) for particle size fractions corresponding to PM2.5 and PM10. The obtained results were compared across different indoor environments and discussed in relation to occupancy and ventilation conditions.

2. MATERIALS AND METHODS

Measurements of indoor air quality were conducted in selected facilities of a university building, including lecture rooms, a library, a laboratory, administrative office and a large hall. The characteristics of the monitored spaces are summarized in Table 1. Airborne particles were measured using an Extech VPC260 portable particle counter. The instrument was used to determine particle number concentrations expressed in particles per liter of air (pcs/L) for particle size fractions corresponding to PM2.5 and PM10. In addition, air temperature and relative humidity were recorded during each measurement. Measurements were carried out according to the manufacturer's instructions. Sampling was conducted before and after educational activities in order to evaluate changes in airborne particle concentrations associated with room use. Measurements performed after educational activities were carried out approximately 30 minutes after the end of lectures. During this period, natural ventilation was applied through window opening or door opening, depending on the characteristics of the monitored space. The monitored spaces exhibited different occupancy levels, ranging from 3 occupants in the library to 200 occupants in the large hall. Measurements were

performed on tables at approximately 0.8–1.0 m above floor level, corresponding to the breathing zone of seated occupants. Information regarding the approximate occupancy of each monitored space and ventilation conditions was recorded during the measurements. The monitored spaces were selected to represent different functional areas within the university building. Lecture rooms were characterized by relatively high occupancy levels, whereas the library and administrative office exhibited lower occupancy. The laboratory represented a specialized educational environment with moderate occupancy, while the large hall was included to assess air quality under conditions of high occupant density during a graduation ceremony. The collected data were subsequently analyzed and compared among different university spaces to identify variations in airborne particle concentrations and to assess the influence of occupancy and ventilation on indoor air quality.

Table 1: Characteristics of the monitored spaces

Location	Area [m²]	Capacity (persons)	Ventilation
Lecture room 5	81.15	108	Door opening
Lecture room 6	113	154	Window opening
Lecture room 7	59.20	47	Window opening
Library	67.20	N/A	Window opening
Laboratory	89.40	14	Door opening
Administrative office	59.20	N/A	Window opening
Large hall	186	200	Window opening

3. RESULTS AND DISCUSSION

3.1. Measured Environmental Parameters and PM2.5 Concentrations

Table 2 and Figure 1 present the measured environmental parameters and PM2.5 particle number concentrations before and after educational activities in selected university spaces. Measurements included lecture rooms, a library, a laboratory, an administrative office, and a large hall. PM10 particle number concentrations were 0 pcs/L in all measurements and were therefore excluded from further analysis.

Table 2: Measured environmental parameters and PM2.5 particle number concentrations before and after educational activities

Location	Occupancy (persons)	Temperature Before [°C]	RH Before [%]	PM2.5 Before [pcs/L]	Temperature After [°C]	RH After [%]	PM2.5 After [pcs/L]
Lecture Room 5	48	23.1	51.3	15	25.0	38.5	27
Lecture Room 6	30	24.8	47.8	19	25.1	38.5	8
Lecture Room 7	42	25.3	44.8	9	24.5	48.5	18
Library	3	24.9	49.3	11	24.5	48.2	15
Laboratory	14	23.1	55.3	9	24.5	53.2	14
Administrative office	4	23.5	44.8	15	24.2	43.6	20
Large Hall*	200	21.0	48.2	11	22.5	48.2	25

* Measurement performed before and after a graduation ceremony.

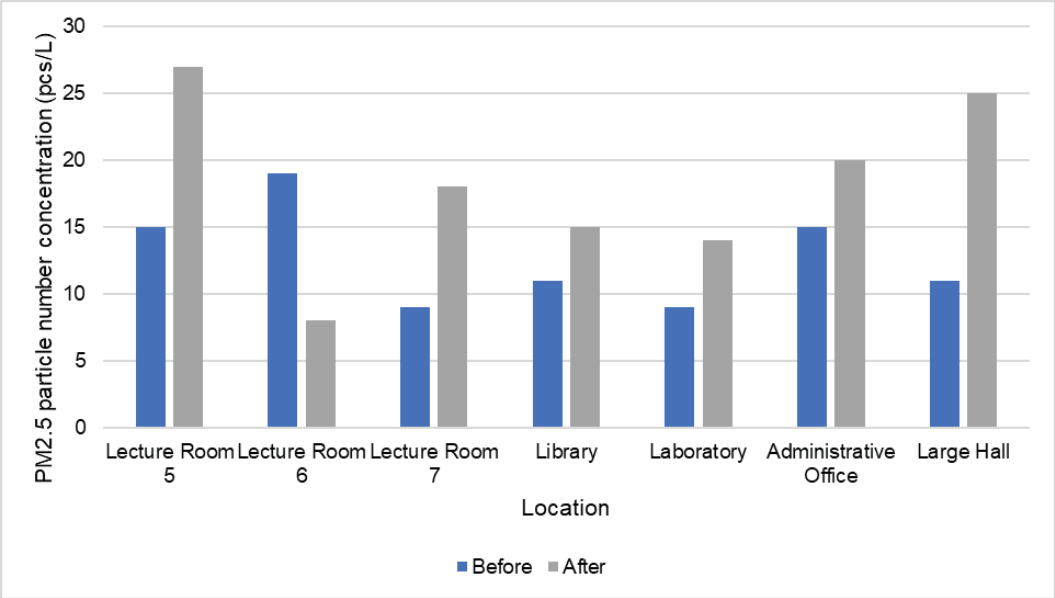


Figure 1: PM2.5 particle number concentrations measured before and after educational activities in selected university spaces

Air temperatures ranged from 21.0 °C to 25.3 °C before educational activities and from 22.5 °C to 25.1 °C after educational activities. Relative humidity values ranged from 44.8 % to 55.3 % before occupancy and from 38.5 % to 53.2 % after occupancy and ventilation. In most monitored spaces, a slight increase in temperature and a decrease in relative humidity were observed after educational activities.

The measured PM2.5 particle number concentrations ranged from 8 to 27 pcs/L. The highest PM2.5 concentration after educational activities was recorded in Lecture Room 5 (27 pcs/L), while the lowest concentration was observed in Lecture Room 6 (8 pcs/L). The results indicate noticeable differences between the monitored spaces. While most locations exhibited an increase in PM2.5 particle number concentrations after educational activities, the magnitude of the observed changes varied considerably.

3.2. Effect of Occupancy and Ventilation on Indoor Air Quality

The observed differences among the monitored spaces suggest that particle concentrations are influenced by a combination of occupancy, room characteristics, and ventilation conditions. Although most monitored locations exhibited an increase in PM2.5 concentrations after educational activities, the magnitude of these changes varied considerably.

Lecture Room 6 represented a particularly interesting case, as PM2.5 concentrations decreased from 19 to 8 pcs/L despite an occupancy of approximately 30 students. This lecture room had the largest seating capacity among the monitored lecture rooms and was ventilated through window opening. The observed decrease may be associated with window ventilation and the larger room size, although the individual contribution of these factors cannot be determined from the present measurements.

Lecture Room 5 showed the highest PM2.5 concentration after educational activities (27 pcs/L). Unlike most monitored spaces, this room relied primarily on door opening rather than window opening for ventilation. The laboratory exhibited similar ventilation characteristics. Although the present

study was not designed to evaluate ventilation efficiency, the results suggest that differences in air exchange may have contributed to the observed variations in particle concentrations.

The monitored spaces also differed substantially in occupancy levels, ranging from 3 occupants in the library to approximately 200 participants in the large hall during a graduation ceremony. Higher occupancy levels may contribute to increased particle concentrations through human activity and the resuspension of settled dust. This effect was particularly evident in the large hall, where PM2.5 concentrations increased from 11 to 25 pcs/L following the event.

Overall, the results indicate that occupancy alone cannot fully explain the observed particle concentrations. Room size, ventilation conditions, and the type of activities performed within the monitored spaces should also be considered when assessing indoor air quality in educational buildings.

3.3. Discussion of Findings

Measurements performed after educational activities were conducted approximately 30 minutes after the end of lectures. Consequently, the measured values represent indoor air conditions following occupancy and ventilation rather than conditions during educational activities. This should be considered when interpreting the results. Despite the relatively high occupancy levels observed in several lecture rooms and in the large hall, PM2.5 concentrations remained relatively low in all monitored spaces. Although the measured particle number concentrations cannot be directly compared with guideline values expressed as mass concentrations (μg/m³), the findings emphasize the importance of considering ventilation conditions when assessing indoor air quality in educational environments [1,5].

The findings are consistent with previous studies highlighting occupancy and ventilation as important factors affecting indoor air quality in educational buildings [4,6,7]. Human activity can contribute to the resuspension of settled particles, while ventilation may influence the accumulation or removal of airborne pollutants. However, the results of the present study indicate that occupancy alone cannot fully explain the observed differences in particle concentrations. For example, in Lecture Room 6, PM2.5 particle number concentrations decreased from 19 to 8 pcs/L after occupancy and window ventilation, whereas in the large hall they increased from 11 to 25 pcs/L following an event attended by approximately 200 participants.

Recent studies provide further support for this interpretation. A 2024 review by Branco et al. [8] identified occupancy and occupant activities, ventilation systems, and building characteristics as relevant parameters when assessing indoor air quality in educational facilities. In a study involving 60 classrooms in London, Kumar et al. [9] reported higher PM2.5 and PM10 concentrations during occupied periods compared with non-occupied periods and observed lower particulate matter concentrations in classrooms using combined mechanical and natural ventilation. Han et al. [10] further showed that indoor PM2.5 concentrations in three elementary schools reflected both outdoor particulate levels and classroom activities, supporting the interpretation that indoor particle concentrations are influenced by multiple interacting sources and processes. Similar observations have also been reported in university environments. Mustață et al. [11], who monitored PM1, PM2.5, PM10, and CO_2 in university indoor spaces with different occupancy levels and natural ventilation conditions, showed that particulate matter concentrations were influenced not only by occupancy but also by occupant movement, room characteristics, and ventilation conditions. These findings are consistent with the results of the present study, where differences in occupancy among the monitored spaces were not accompanied by proportional differences in PM2.5 particle number concentrations.

Overall, the comparison with previous studies indicates that the observed particle concentrations should be interpreted as the result of several interacting factors rather than occupancy alone. Room characteristics, ventilation conditions, the type of activities performed within the space, and potential outdoor sources may all contribute to variations in indoor particulate matter concentrations. Therefore, the differences observed among the monitored university spaces cannot be attributed to a single parameter.

A limitation of the present study is the relatively small number of measurements and the fact that monitoring was performed in a single university building. Furthermore, measurements after educational activities were conducted following a period of ventilation, which may have influenced particle concentrations compared with conditions during occupancy. Future studies could include continuous monitoring during lectures and additional indoor air quality indicators, such as carbon dioxide concentrations and ventilation rate parameters. Repeated measurements over longer periods would also provide a more comprehensive assessment of temporal variations in indoor air quality and the relative influence of occupancy and ventilation conditions.

4. CONCLUSION

This study assessed indoor air quality in selected university spaces by measuring airborne particle number concentrations before and after educational activities. Measurements were conducted in lecture rooms, a library, a laboratory, an administrative office, and a large hall using a portable particle counter. The results showed differences in PM2.5 particle number concentrations among the monitored spaces, while no PM10 particles were detected during the measurements (0 pcs/L).

Changes in PM2.5 particle number concentrations varied considerably between the monitored spaces. The highest concentration after educational activities was recorded in Lecture Room 5 (27 pcs/L), while Lecture Room 6 showed a decrease from 19 to 8 pcs/L following occupancy and window ventilation. In the large hall, the concentration increased from 11 to 25 pcs/L after an event attended by approximately 200 participants. These differences indicate that occupancy alone cannot fully explain the observed variations in particle concentrations.

The findings suggest that indoor particle levels in educational environments should be considered in relation to several interacting factors, including occupancy, room characteristics, occupant activities, and ventilation conditions. The observed variations among the monitored spaces also demonstrate the usefulness of particle number measurements for assessing differences in indoor environmental conditions.

The study was limited to a single university building and a relatively small number of measurements. Future studies should include continuous and repeated measurements over longer periods, particularly during occupancy, together with additional indoor air quality parameters such as carbon dioxide concentrations and ventilation rates. Such monitoring could provide a more comprehensive assessment of indoor air quality and support decisions related to ventilation and indoor environmental management in educational facilities.

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Review article

RISK ASSESSMENT OF CHEMICAL HAZARDS IN PLANT-BASED BEVERAGES

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Abstract: *Plant-based beverages represent a rapidly growing category of food products driven by increasing consumer demand. Their safety may be affected by chemical hazards associated with raw materials. This study aimed to assess the risk posed by selected chemical hazards in plant-based beverages, including heavy metals, pesticide residues, and mycotoxins. Risk assessment was conducted following the standard four-step framework comprising hazard identification, hazard characterization, exposure assessment, and risk characterization. The results indicate that heavy metals and pesticide residues are unlikely to pose a significant health risk under current exposure scenarios. In contrast, mycotoxins, particularly deoxynivalenol (DON), may represent a potential health concern, especially for vulnerable population groups such as children. These findings emphasize the importance of ensuring raw material quality and implementing continuous monitoring of chemical hazards to maintain product safety.*

Keywords: *chemical hazards, mycotoxins, plant-based beverages, risk assessment, food safety*

1. INTRODUCTION

Plant-based beverages have experienced a substantial increase in popularity in recent years and represent one of the fastest-growing categories of food products. Growing consumer demand has driven the development of a wide range of products derived from various plant sources, predominantly cereals, legumes, nuts, and seeds. Given their increasing presence in consumers' diets, the quality and safety of these products have become important considerations throughout the production process.

The production of plant-based beverages commonly relies on oats, rice, soybeans, almonds, coconut, hazelnuts, and other plant-derived raw materials. The quality of these ingredients significantly influences the characteristics of the final product, while various forms of contamination may occur during cultivation, storage, and processing. Therefore, the identification and control of potential hazards are essential for ensuring food safety throughout the entire production chain [1].

Among the chemical hazards most commonly associated with plant-based beverages are heavy metals, pesticide residues, and mycotoxins. Heavy metals such as arsenic, cadmium, lead, and mercury may enter raw materials through contaminated soil, water, or other environmental sources

and subsequently persist in the final product. Pesticide residues are associated with the use of plant protection products during agricultural production, whereas mycotoxins are secondary metabolites produced by toxigenic moulds that can contaminate cereals, legumes, and nuts during cultivation or storage [2–4].

Given the continuous growth in the consumption of plant-based beverages and the increasing focus on their safety, it is essential to monitor the occurrence of chemical hazards and assess their potential impact on consumer health. Therefore, the aim of this study was to review the available evidence regarding the occurrence of heavy metals, pesticide residues, and mycotoxins in plant-based beverages and to evaluate their relevance in the context of food safety and consumer risk assessment.

2. CHEMICAL HAZARDS IN THE PRODUCTION OF PLANT-BASED BEVERAGES

Chemical hazards in the production of plant-based beverages are primarily associated with the raw materials used in their manufacture. Their presence may result from environmental contamination, agricultural practices, or the growth of moulds during the cultivation and storage of raw materials. Unlike many microbiological hazards that can be effectively controlled through thermal processing, chemical hazards often persist after processing and may consequently be transferred to the final product [1, 2].

2.1. Heavy Metals

Heavy metals constitute a group of chemical contaminants that occur naturally in the environment; however, their concentrations may increase as a result of anthropogenic activities such as industrial production, transportation, and intensive agricultural practices. Due to their persistence in the environment and their ability to accumulate in plant tissues, heavy metals may enter the food chain and pose a potential risk to consumer health. In the production of plant-based beverages, particular attention is given to the contamination of raw materials, as plants can absorb metals from soil, irrigation water, and other environmental sources during growth.

Among the heavy metals that may be present in raw materials used for the production of plant-based beverages, arsenic (As), cadmium (Cd), and lead (Pb) are of particular concern. Their significance stems from their potential adverse effects on human health, including neurotoxicity, nephrotoxicity, carcinogenicity, and other chronic effects associated with long-term exposure. Although the concentrations of these elements in plant-based beverages are generally found to be below established regulatory limits, their presence requires continuous monitoring due to the regular consumption of these products and their increasing presence in consumers' diets.

Previous studies have shown that rice-based beverages generally contain higher concentrations of As compared with products derived from other plant sources. These findings are attributed to the ability of rice to accumulate As from soil and water during cultivation, which is why rice products are frequently identified as one of the major dietary sources of inorganic As exposure [5, 6].

Elevated concentrations of As have also been reported in certain oat-based beverages, with observed levels varying considerably depending on the origin of the raw material and cultivation conditions. Despite this variability, the concentrations detected in most analysed products remained within regulatory limits [6].

Table 1: Most commonly identified heavy metals in raw materials used for the production of plant-based beverages [2, 5–8].

Raw material	Reported heavy metals	Remarks
Rice	As	High As accumulation; higher concentrations than in most other plant-based raw materials.
Oats	As, Cd	Concentrations vary according to raw material origin and cultivation conditions.
Soybeans	Cd, Pb	Concentrations vary according to the geographical origin of the raw material.
Almonds	Cd	Some studies indicate an increased potential for Cd accumulation.
Coconut	As, Cd, Pb	Generally associated with a lower risk of heavy metal contamination.
Other nuts	Cd, Pb	Generally lower concentrations compared with rice.

Soy-based beverages are most commonly associated with the presence of Cd and Pb. Reported concentrations of these metals vary among manufacturers and production regions, highlighting the importance of raw material quality and effective control measures throughout the production chain [7].

Coconut- and nut-based beverages are generally considered to present a lower risk of heavy metal contamination. Studies have shown that the concentrations of the analysed metals in beverages produced from these raw materials are typically low and do not represent a significant contribution to overall dietary exposure [8].

Available evidence indicates that the type of raw material used is one of the key factors determining the level of heavy metal contamination in plant-based beverages. Particular attention is focused on rice-based products because of their greater tendency to accumulate As, whereas the concentrations of analysed metals in beverages produced from other plant sources generally remain within acceptable regulatory limits. These findings emphasise the importance of continuous monitoring of both raw materials and finished products to ensure food safety and consumer protection.

2.2. Pesticide Residues

Pesticides are widely used in agricultural production to protect crops from weeds, pests, and plant diseases and play an important role in maintaining crop yield and raw material quality. However, their use may result in the presence of residues in food products, particularly in cases of improper application or non-compliance with good agricultural practices. As plant-based beverages are produced from a variety of cereals, legumes, and nuts, pesticide residues represent one of the chemical hazards that require continuous monitoring and safety assessment [2].

Residues of various classes of pesticides, including herbicides, fungicides, and insecticides, may be present in raw materials used for the production of plant-based beverages. Their occurrence depends on the crop species, production intensity, climatic conditions, and agricultural practices employed. Although processing may reduce or eliminate a portion of these residues, certain amounts may remain in the final product, making them a subject of routine monitoring and regulatory oversight [1, 2].

Previous studies have shown that pesticide residues are most frequently detected in products derived from cereals and legumes, with oats, rice, and soybeans among the most extensively investigated raw materials. Analyses of commercially available products have identified several

active substances, including piperonyl butoxide, pirimiphos-methyl, and fipronil sulfone. Although these compounds were detected in certain samples, their concentrations were low and did not indicate an increased risk to consumers [1].

Rice is often identified as a raw material requiring particular attention because of the intensive use of plant protection products during cultivation. Oat- and soy-based beverages may also contain various pesticide residues; however, the concentrations reported in most studies remain low. Differences observed among products highlight the importance of raw material origin, agricultural production practices, and quality control systems throughout the production chain [1, 2].

Several recent studies did not detect measurable concentrations of pesticide residues in the analysed samples of plant-based beverages. This may be partially explained by the relatively low proportion of plant-derived raw materials in the final product, as well as by dilution effects occurring during processing [7]. These findings suggest that the presence of plant raw materials does not necessarily result in increased exposure to pesticide residues, as the final concentrations largely depend on the origin of the raw materials, agricultural management practices, and processing technologies applied.

Overall, the available evidence indicates that pesticide residues may occur in various raw materials used for the production of plant-based beverages, with their occurrence and concentrations being primarily influenced by agricultural practices and raw material origin. Although current studies generally do not indicate significant consumer exposure, continuous monitoring remains an important tool for confirming product safety and for the timely identification of potential deviations from established safety standards.

2.3. Mycotoxins

Mycotoxins are secondary metabolites produced by moulds that can contaminate agricultural crops during cultivation, harvesting, storage, and processing. Their occurrence in food represents a significant food safety challenge due to their toxicity and the potential adverse effects they may have on human health. As plant-based beverages are produced from raw materials such as cereals, legumes, and nuts, the presence of mycotoxins in these raw materials may result in their transfer to the final product.

Among the mycotoxins most commonly associated with the production of plant-based beverages are aflatoxins, deoxynivalenol (DON), zearalenone (ZEA), fumonisins, ochratoxin A (OTA), and the trichothecenes T-2 and HT-2 toxins. In recent years, particular attention has also been given to so-called emerging mycotoxins, such as enniatins and beauvericin, which are increasingly detected in plant-derived products but are not yet fully addressed within current regulatory frameworks [7].

Previous studies have shown that cereals, particularly oats and rice, are among the raw materials carrying the highest risk of mycotoxin contamination. Analyses of commercially available plant-based beverages have revealed the presence of various mycotoxins, with DON, enniatins, and beauvericin among the most frequently detected compounds. In a study conducted on samples collected in Latvia and Lithuania, at least one mycotoxin was detected in 61% of the analysed products, while DON, beauvericin, and enniatins A, B, and B1 were the most prevalent contaminants [9].

A recent study investigating 100 plant-based beverages demonstrated a frequent occurrence of mycotoxins associated with the type of raw material used. Oat-based beverages most commonly contained DON and T-2 and HT-2 toxins, whereas higher concentrations of Alternaria toxins and aflatoxins were reported in almond- and hazelnut-based beverages [10].

Oat-based beverages are particularly notable as a product category in which mycotoxins are frequently detected. Several studies have identified DON, aflatoxins, T-2 and HT-2 toxins, OTA, and ZEA, although the concentrations reported were generally relatively low. The occurrence of DON has been confirmed in multiple oat-based beverage samples and is associated with the frequent contamination of oats by Fusarium species during cultivation and storage [7, 9].

Mycotoxin contamination is not limited to oats. Traces of aflatoxins and other mycotoxins have also been reported in soy-, rice-, and almond-based products, while some studies have demonstrated the simultaneous presence of multiple mycotoxins within the same product. This co-occurrence is particularly relevant from a food safety perspective, as the potential synergistic effects of exposure to multiple mycotoxins remain insufficiently understood [7].

On the other hand, several recent studies did not detect mycotoxins in the analysed samples of plant-based beverages, indicating that raw material quality, climatic conditions, and production practices have a substantial influence on the final level of contamination. Nevertheless, the available literature confirms that the transfer of mycotoxins from raw materials to the final product represents a realistic risk and that their presence should be continuously monitored throughout the entire production chain [7].

As shown in Table 2, the occurrence of mycotoxins largely depends on the type of raw material used in the production of plant-based beverages. Cereals, particularly oats and rice, are frequently associated with contamination by mycotoxins produced by *Fusarium* species, whereas aflatoxins are the primary concern in nuts. Therefore, effective raw material quality control represents one of the key prerequisites for successful management of mycotoxin-related risks in this product category.

Table 2: Mycotoxins most frequently reported in raw materials used for the production of plant-based beverages [7,9,11].

Raw material	Reported mycotoxins	Remarks
Oats	DON, T-2, HT-2, ZEA, OTA	Most studied raw material; often linked to mycotoxin contamination.
Rice	DON, aflatoxins	Risk depends mainly on climate and storage conditions.
Soybeans	Aflatoxins, enniatins	Potential co-occurrence of multiple mycotoxins.
Almonds	Aflatoxins	Storage-related contamination.
Other nuts	Aflatoxins	Aflatoxins are the main food safety concern.
Mixed raw materials	DON, beauvericin, enniatins	Frequent co-occurrence of multiple mycotoxins.

3. RISK ASSESSMENT OF CHEMICAL HAZARDS IN PLANT-BASED BEVERAGES

A review of the available literature indicates that heavy metals, pesticide residues, and mycotoxins may occur in raw materials used for the production of plant-based beverages. Their presence is regulated by European legislation establishing maximum permitted levels of contaminants in food, while their health significance is assessed by comparing measured concentrations with toxicological reference values [4, 12].

From a food safety perspective, heavy metals and mycotoxins require particular attention. Rice-based beverages frequently exhibit higher concentrations of As compared with products derived from other plant sources, while Cd, Pb, and other metals may also be present in different types

of plant-based beverages depending on the origin of the raw material and production conditions [5,6,8]. At the same time, cereals and other plant-derived raw materials are susceptible to mycotoxin contamination during cultivation and storage. These contaminants may subsequently be transferred to the final product and remain present even after processing [4, 9].

The available evidence suggests that heavy metals and mycotoxins are the chemical hazards contributing most substantially to the overall risk associated with the production of plant-based beverages. Their significance arises from their association with raw materials and their potential transfer to the final product. In contrast, pesticide residues have generally been reported at low concentrations, and their contribution to the overall risk assessment is considered to be comparatively lower [1, 7].

Although the concentrations of the analysed contaminants reported in most studies remained within established regulatory limits, continuous monitoring of both raw materials and finished products remains essential for the timely identification of potential deviations and effective risk management. Therefore, risk assessment and the systematic monitoring of chemical contaminants are considered important tools for ensuring the safety of plant-based beverages and protecting consumer health.

4. CONCLUSION

Chemical hazards in plant-based beverages are primarily associated with the raw materials used in their production. A review of the available literature identified heavy metals, pesticide residues, and mycotoxins as the most relevant contaminants, with their occurrence and concentrations depending on the type of raw material, cultivation and storage conditions, and the production practices applied.

Heavy metals and mycotoxins appear to be of greatest significance in the context of plant-based beverage safety. Rice is recognised as a raw material with a greater tendency to accumulate As, whereas cereals, particularly oats, are more frequently associated with mycotoxin contamination, including DON and T-2 and HT-2 toxins. In contrast, pesticide residues have generally been detected at low concentrations in most analysed products and are therefore considered to contribute less to the overall risk.

Although the concentrations of the analysed contaminants reported in most studies remained within established regulatory limits, their presence highlights the need for continuous monitoring of both raw materials and finished products. Raw material quality represents a key factor in the control of chemical hazards, as many contaminants may be transferred to the final product and remain present after processing.

Current evidence suggests that plant-based beverages do not pose a significant risk to consumers. Nevertheless, the continuous growth in the production and consumption of these products emphasises the importance of regular monitoring of chemical contaminants and the implementation of risk-based food safety systems to maintain a high level of safety for plant-based beverages available on the market.

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Original scientific paper

ASSESSMENT OF GENERATION AND EXPOSURE TO ASA FILAMENT DUST PARTICLES DURING FDM 3D PRINTING: MICROSCOPIC ANALYSIS AND OCCUPATIONAL SAFETY RECOMMENDATIONS

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Abstract: *FDM 3D printing is becoming an increasingly widespread technology, but the generation of dust particles during the process can pose a risk to workers health. In this study, dust produced from printing ASA filament was analyzed using microscopic techniques. Dust samples were collected from the work surface and printer filters and characterized in terms of particle size, shape, and aggregation. The results indicate the presence of respirable particles, with potential for respiratory irritation. Based on these findings, occupational safety measures are proposed, including local exhaust ventilation, HEPA filtration, the use of personal protective equipment, and administrative procedures to reduce exposure. This study contributes to the understanding of EHS risks associated with 3D printing and provides practical guidelines for safer laboratory practices.*

Keywords: *FDM 3D printing, ASA filament dust, respirable particles, microscopic analysis, occupational safety*

1. INTRODUCTION

Fused Deposition Modeling (FDM) 3D printing has become an increasingly popular manufacturing technology in both industrial and laboratory environments. Despite its advantages, the process can generate airborne dust and ultrafine particles from thermoplastic filaments, which may pose potential

health risks to workers and laboratory personnel. Experimental studies have shown that particulate emissions from 3D printing include ultrafine particles that vary with the type of printer and material, and that attention must be given to potential health risks in research and indoor environments [1].

Among commonly used filaments, ASA (Acrylonitrile Styrene Acrylate) is favored for its mechanical and weather-resistant properties, yet its dust emissions during printing have not been extensively studied in the context of occupational safety. Research indicates that nanoparticulate emissions from 3D printers can differ based on printer type and printing material, and that these particles may vary in morphology and composition, emphasizing the need for exposure assessment [1]. In addition, consolidated chamber studies have documented that material extrusion 3D printing emits significant amounts of airborne particles and volatile organic compounds that contribute to indoor particulate burden [2]. Regulatory and research organizations recognize that emissions from desktop 3D printing can include respirable ultrafine particles, underscoring occupational health considerations for long-term exposure [3].

This study aims to assess the generation and characteristics of ASA filament dust during FDM 3D printing and to evaluate the potential exposure risk for operators. Dust samples were collected from work surfaces and printer filters and analyzed microscopically to determine particle size, shape, and aggregation. The findings provide insights into the respirable fraction of particles and their implications for respiratory health. Based on these results, practical recommendations for occupational safety, including local exhaust ventilation, HEPA filtration, and personal protective equipment, are proposed to minimize exposure and ensure safer laboratory practices.

2. MATERIAL AND METHODS

This experimental study was conducted to investigate and characterize dust particles generated during FDM 3D printing of ASA filament, focusing specifically on particle size, shape, and aggregation. These characteristics are critical in evaluating potential occupational exposure, as they determine the respirability of particles, their behavior in the air, and their deposition within the respiratory system. Dust samples were collected from the printer work surface and internal filters, and subsequently analyzed using microscopic techniques. The experimental setup was designed to replicate typical laboratory printing conditions while maintaining controlled and reproducible parameters.

2.1. Material

The filament used was ASA (Acrylonitrile Styrene Acrylate), 1.75 mm in diameter, chosen for its widespread laboratory use due to mechanical strength, UV resistance, and dimensional stability [1]. ASA is particularly relevant in this context because its thermal and mechanical properties may influence particle emission patterns during FDM printing.

Printing parameters were carefully standardized: a 0.2 mm nozzle, extrusion temperature of 260 °C, and heated bed temperature of 90 °C were applied, in accordance with manufacturer specifications. Standardization of these parameters ensures reproducibility and allows consistent assessment of particle generation.

2.2. Sample collection

Dust particles were collected from two primary locations:

1. Printer work surface: particles that settled on the surrounding surfaces during print jobs (*n*=4).
2. Internal printer filter: particles captured by the printer's filtration system, representing airborne fractions not immediately settling on surfaces (*n*=1).

Each experiment involved a 44-hour printing process, after which dust particles were collected from the surface of the build platform and from the internal filter, with sampling conducted twice. Sampling was performed using adhesive tape, which was then transferred onto clean microscope slides.

Multiple samples (Figure 1) were collected per print job to ensure statistical reliability.

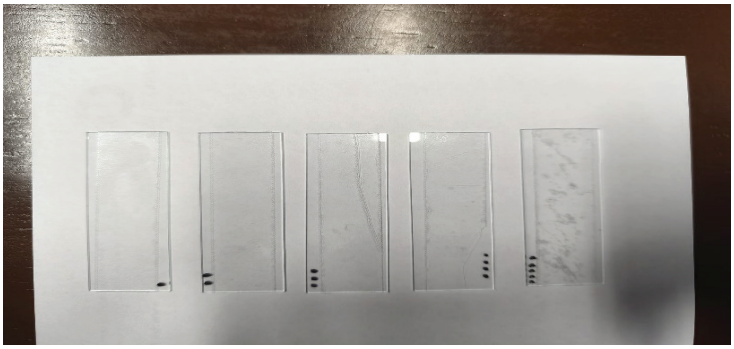


Figure 1. Samples for microscopic analysis.

2.3. Instrumentation and Microscopic Analysis

Dust samples were analyzed using an optical microscope PME OLYMPUS TOKYO (Figure 2). The microscope was equipped with a digital camera system, allowing high-resolution image acquisition and subsequent analysis. Image processing and particle measurements were performed using dedicated software (DinoCapture 2.0), enabling accurate determination of particle dimensions and morphology.

The microscope was calibrated prior to analysis using reference calibration slides with known particle sizes to ensure measurement accuracy and reproducibility.

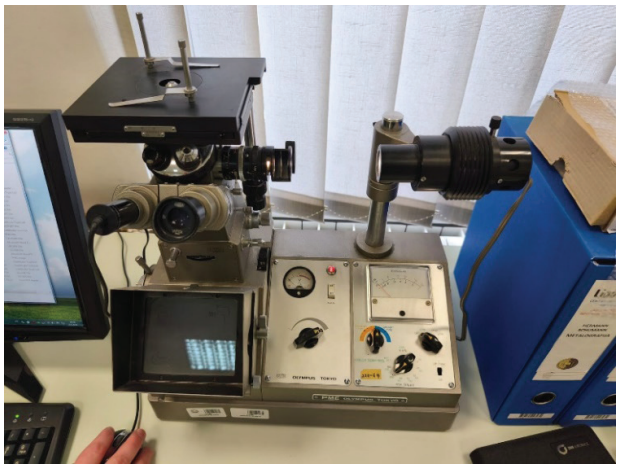


Figure 2. Optical microscope PME OLYMPUS TOKYO.

Dust samples were analyzed with an optical microscope at magnifications up to 500×, focusing on three key characteristics:

1. Particle size: The size of individual particles was measured using digital image analysis software [4, 5].
2. Particle shape: Particles were classified as spherical, irregular, or fiber-like [6].
3. Aggregation: Particle aggregation was observed to assess clustering [6].

Statistical metrics such as mean and standard deviation were calculated to summarize particle characteristics.

3. RESULTS

3.1. Microscopic observations

Representative microscopic images of ASA dust particles collected from the build platform and the internal printer filter are shown in Figure 3. All observed particles exhibited a predominantly spherical shape, with no elongated or irregular forms detected. No aggregation of particles was observed; each particle appeared as a distinct, individual unit. This indicates that ASA filament dust consists of discrete, round particles with uniform morphology, which simplifies the assessment of respirable fractions and occupational exposure potential.

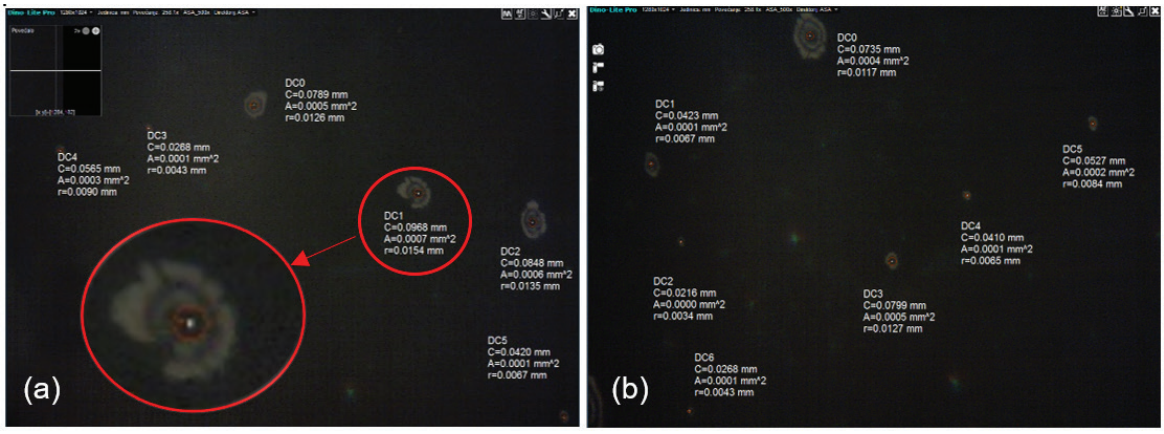


Figure 3. Microscopic images of ASA dust particles collected from (a) the build platform and (b) the printer filter.

3.2. Particle size and density analysis

Quantitative analysis of the collected ASA dust particles was performed to determine particle size and density. For each sample, multiple fields of view (n=5) were imaged, and digital image analysis was applied to quantify particle dimensions, shape distribution, and aggregation degree.

The results are summarized in Table 1. Particle diameters ranged from 5,2 µm to 73,6 µm on the build platform, with an average diameter of 24,9 ± 12,6 µm. Particles collected from the printer filter were slightly smaller, ranging from 6,8 µm to 35,8 µm, with an average diameter of 20,1 ± 8,1 µm.

The particle density, expressed as the surface of particles per unit area on the microscope slide, was obtained as the sum of values from five sampling locations. At each location, density was calculated by dividing the total particle area by the microscope field of view area (2 × 2 mm). The measured particle density was higher on the build platform (0,09 ± 0,04 %) than on the printer filter (0,04 ± 0,02 %).

Table 1. Particle size distribution and density of ASA dust particles collected from the build platform and printer filter.

	Sample 1 (middle of platform)	Sample 3 (middle of platform)	Sample 2 (end of platform)	Sample 4 (end of platform)	Sample 5 (printer filter)
Average diameter ± SD (µm)	25,5 ± 14,2	24,3 ±10,8	26,7 ± 15,3	23,9 ± 11,4	20,1 ± 8,1
Density ± SD (%)	0,08 ± 0,04	0,10 ± 0,05	0,09 ± 0,06	0,10 ± 0,03	0,04 ± 0,02

3.3. Distribution of respirable and non-respirable particles

The distribution of particles by size was further analyzed to distinguish respirable particles (≤10 µm) from larger particles (>10 µm) across individual microscope slides. Two bar graphs (Figure 4) illustrate the particle counts for each slide collected from the middle of build platform and the end of build platform.

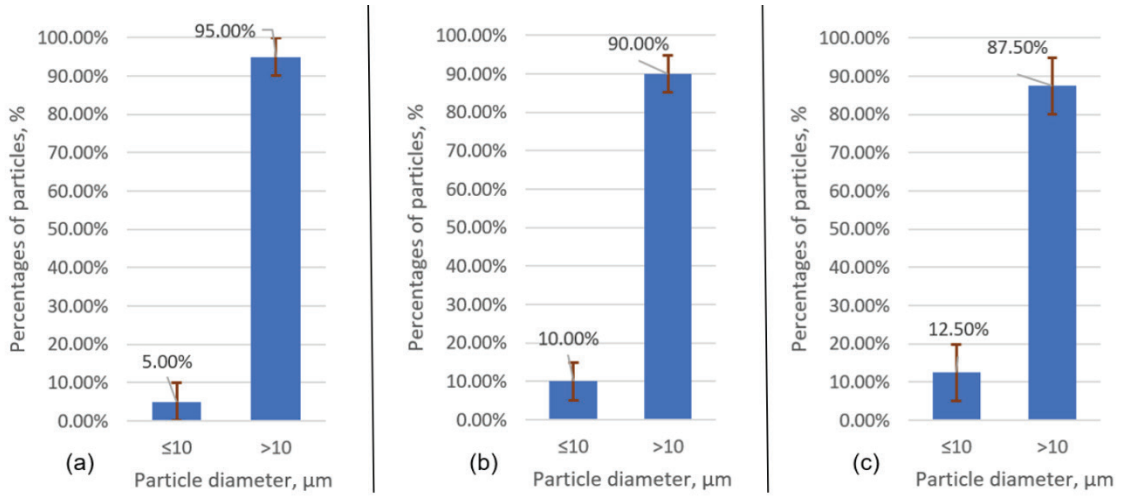


Figure 4. Percentages of respirable (≤10 µm) and non-respirable (>10 µm) particles per microscope slide collected from (a) the middle of build platform, (b) the end of build platform and (c) printer filter

3.4. Discussion of Results

The microscopic and quantitative analyses demonstrate that ASA filament dust generated during FDM printing consists exclusively of spherical, discrete particles, with no elongated or aggregated forms.

Particular attention was paid to respirable particles (≤10 µm), which can penetrate deep into the alveolar regions of the lungs [4, 5]. Analysis of the build platform samples shows a lower number of respirable particles at the center of the platform, likely due to airflow from the printer's fan dispersing smaller particles away from the central area. In contrast, samples from the outer regions

of the platform contained higher counts of respirable particles, indicating preferential deposition where airflow effects were reduced. Filter samples showed slightly higher proportions of respirable particles, confirming that ultrafine particles remain suspended in the air and are captured by the filtration system; however, greater suction power would likely improve its effectiveness.

Shape affects aerodynamic behavior, deposition in the respiratory tract, and potential adherence to mucosal surfaces. Irregular and elongated particles may remain airborne longer and increase the risk of inhalation exposure [6]. Although all particles are spherical, the presence of respirable particles highlights the potential for inhalation exposure, emphasizing the need for proper laboratory safety measures.

Particle aggregation was observed to assess clustering, which affects both the aerodynamic diameter and the probability of deep lung deposition. Aggregates may disaggregate under airflow, producing respirable fragments [6]. Since the particles are not aggregated, their movement in air is easier to predict, but small respirable particles can still pose a health risks.

These findings on particle size, shape, and aggregation directly inform occupational safety recommendations. Respirable particles, especially those below 10 μm, pose inhalation risks, while fiber-like or irregular particles may increase deposition in sensitive regions of the respiratory system. Aggregated particles may alter deposition patterns and influence both acute and chronic exposure [1, 5].

Based on these insights, practical mitigation strategies include:

- Local exhaust ventilation to remove airborne particles at the source,
- HEPA filtration to capture fine and ultrafine particles,
- Personal protective equipment (PPE) such as respirators, gloves, and lab coats,
- Administrative controls, including limiting exposure duration, regular cleaning, and continuous monitoring of particle deposition.

Overall, the findings provide a clear characterization of ASA dust in terms of size, density, and morphology, forming a basis for assessing occupational risk and informing safe handling practices in 3D printing laboratories.

4. CONCLUSION

This study investigated dust particles generated during FDM 3D printing of ASA filament, with a focus on particle size, morphology, and spatial distribution. The results indicate that ASA filament produces discrete, spherical dust particles during the FDM process, as reported in this study.

Particle size and respirability analysis revealed that respirable particles (≤10 μm) were present both on the build platform and in the printer filter. Particles collected from the filter were generally smaller, whereas particles on the build platform included both larger particles (>10 μm) and a fraction of smaller respirable particles.

Spatial distribution results indicated that the number of respirable particles was lower at the center of the build platform, most likely due to airflow generated by the printer fan dispersing fine particles, while higher concentrations were observed in peripheral areas.

Occupational exposure assessment suggests that, despite the absence of aggregates, respirable particles may still pose an inhalation hazard. Therefore, the use of engineering controls such as local exhaust ventilation, HEPA filtration, and personal protective equipment (PPE) is recommended to minimize exposure.

Overall, ASA filament dust consists of discrete, spherical particles with predictable behavior, but small respirable particles are present across both the platform and filter, emphasizing the need for safety precautions in FDM 3D printing laboratories.

Future studies should include real-time aerosol measurements and comparative analysis of different FDM materials and printing parameters, combined with airflow modeling to better understand particle dispersion and occupational exposure dynamics.

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Professional paper

OCCUPATIONAL HEALTH AND SAFETY RISK ASSESSMENT FOR THE ORGANIZATION OF SPORTS COMPETITION

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Abstract: *This study analyzes the importance of occupational health and safety during the organization of sports competitions, with a focus on identifying and assessing the risks faced by workers, volunteers, technical staff and other collaborators. The study covers the legal framework of occupational health and safety in the Republic of Croatia, the risk assessment process, identification of potential hazards in sports facilities and event locations, as well as the implementation of preventive measures to reduce risks. Through the analysis of a real example of a sports event, specific situations and safety measures necessary to protect the health and safety of all participants are presented. The aim of this study is to highlight the necessity of a systematic approach to safety in the organization of sports events and to encourage greater compliance with safety standards in practice.*

Keywords: *occupational health, safety, risk assessment, sport events*

1. INTRODUCTION

Today, sports competitions are increasingly complex and demanding events that involve a large number of people, various equipment and a range of organizational activities. The preparation of such events is not only about the sport itself, but also about creating a safe environment for everyone involved, from the organizers, technical and support staff, to volunteers and external collaborators. This is why it is very important to properly implement occupational safety measures and anticipate possible dangers in a timely manner.

Occupational safety at sports competitions refers to various tasks such as setting up equipment, working at height, power management, securing the area and controlling the audience. Such jobs carry many risks that, if not recognized in time, can lead to injuries, damage to property or even

endanger someone's life. Risk assessment is a key tool in identifying hazards in the workplace and in adopting measures to reduce or eliminate them. When used in the organization of sports events, it helps protect the health of all workers and contributes to a better and safer organization of the event itself. Organizers must take care of the safety of all participants and all engaged workers should be familiar with the rules of occupational safety, which includes regular employee training. Furthermore, the equipment must be in good working order and properly installed, and any risk that is noticed must be reported immediately to the responsible person.

The aim of this paper stems from the above, which is to demonstrate the importance of conducting a risk assessment as part of occupational safety and health when organizing sports competitions.

2. SPORTS AND SPORTS COMPETITIONS

Sport is a complex social system that includes various participants from sports associations, federations, institutions to individuals. Within this system, sports competitions occupy a special place as an organized form of sports expression and achievement. According to Bartoluci, sports management includes the coordinated planning, organization, management and control of sports activities, where sports competitions require top-notch organization, management and control of sports activities and a high degree of professionalism. Special emphasis is placed on logistics, infrastructure and human resources involved in the preparation of events. The safety of competitions, spectators and staff is becoming a key aspect in the implementation of events, which requires systematic risk assessment and the implementation of preventive measures [1].

Throughout history, each new phase of sports competitions has brought its own rules and standards, which have enabled a higher degree of safety and fair play of competitions. A modern sports event often includes strict protocols and supervision to reduce injuries and dangers to participants. Technological advances have enabled more precise organization and monitoring of competitions, which further contributes to safety. Also, the education of participants and volunteers has become an integral part of event preparation. The history and development of sports competitions show that continuous adaptation of rules and protective measures is key to maintaining the safety and integrity of sporting events [2].

The organizer is obliged to take all necessary measures to prevent harmful consequences during the event. Special attention should be paid to the risk assessment related to the venue, technical equipment and audience flow, as well as to the establishment of protocols for emergency interventions in the event of injuries or other unforeseen events [3].

The organization of sports events, depending on the level of competition and the number of participants, is often a complex task that requires thorough planning and precise preparation to make the event successful, regardless of the type of sport and the size of the event, and therefore it is important to start planning on time. The key steps in planning sports competitions are: defining the goals, purpose and type of competition; regulations, permits and documentation; participants, location and time; financial planning; human resources and marketing and promotion of the competition [4].

3. RISK ASSESSMENT IN ORGANIZING SPORTS COMPETITIONS

Risk assessment is a procedure that determines the level of danger, harm and effort in terms of the occurrence of an injury at work, occupational disease, work-related illness and disruption in the work process that could cause harmful consequences for the safety and health of workers. Risk assessments can be prepared by persons authorized to prepare risk assessments. Risk assessments for their own needs can be prepared by the employer [5].

Risk assessment at sporting events plays a key role in ensuring the safety of all participants, spectators and staff. It enables the identification of potential threats and hazards and the planning of appropriate measures to prevent them. For event organisers, risk assessment helps to improve safety protocols, coordinate with police and emergency services and ensure the proper implementation of all activities during the competition. Risk assessment also helps to anticipate and manage unforeseen situations, including violence, crowds, technical failures or natural disasters. An integrated approach, which includes all relevant organisers, police, local authorities and emergency services, reduces the possibility of incidents and enables a faster and more effective response in the event of their occurrence. In this way, risk assessment not only meets legal and convention requirements, but also contributes to the creation of a safe and predictable environment, increases the confidence of participants and spectators and enables the smooth running of sporting events. It is important to emphasise that risk assessment is not only a legal obligation but also the ethical responsibility of all those involved in the organisation of sporting events. It enables the timely identification of potential problems and the implementation of measures that can prevent accidents. By properly assessing risk, organizers can improve safety standards and create a safe environment, increasing participant satisfaction and confidence [6].

3.1. Types of risks in the organization of sports competitions

- **Injuries:** falls, impacts or strains due to improper execution of exercises or accidents during the activity
- **Ergonomic risks:** repetitive movements or incorrect body positions that can lead to musculoskeletal injuries
- **Psychosocial risks:** stress, anxiety or other metal problems that can arise from improperly conducting workshops or an unsafe environment
- **Organizational risks:** lack of appropriate instructor training, poor communication or inadequate preparation of the space for activities
- **Equipment and space-related risks**: inadequate or damaged equipment, unsuitable or unsecured spaces for activities
- **Health risks:** insufficient emergency preparedness (first aid), possible spread of infectious diseases among participants
- **Risks from external influences:** adverse weather conditions (for outdoor activities), unexpected external events that can threaten safety [7].

3.2. Risk assessment methods adapted to sports competitions

According to the Ordinance on the preparation of risk assessment (OG 112/14), the assessment is based on the application of a risk matrix, which combines two basic elements: the probability of a harmful event occurring and the consequences that may arise. On this basis, risks are classified

into three basic categories: low, medium and high risk. Such a classification allows a clear overview of the levels of danger and the determination of priorities in taking protective measures.

The minimum content of each risk assessment includes a list of possible sources of danger, identification of persons and resources that may be at risk, an assessment of probability and consequences, and a proposal for risk reduction measures. In this way, a systematic approach is ensured and the possibility of overlooking important factors is reduced.

The Ordinance recognizes several methods that can be used in the assessment. These are qualitative methods, which rely on the description and ranking of risks, quantitative methods, which present the risk using numerical values, and combined methods, which combine descriptive and numerical approaches. After the hazard has been identified, each risk is assessed according to the probability and severity of the consequences.

The most common methods include:

- **Qualitative assessment:** descriptive assessments of low, medium or high-level risks.
- **Quantitative assessment:** a numerical matrix that combines the probability and consequences of risks for precise prioritization
- **Check-list methods:** regulations of potential hazards adapted to the specific sport and type of competition [5].

4. MEASURES FOR RISK REDUCTION AND ELIMINATION IN SPORTS COMPETITIONS

The risks to which employees are exposed are among the most critical ones that companies must manage—whether by avoiding, reducing, transferring, or accepting and financing them. Although the relevant research focuses on machining processes, the approach and methodology can be effectively applied to the organization of sports competitions, where risks are often associated with large numbers of participants, physical exertion, equipment, and the presence of spectators. In the context of sports, risk identification and assessment are crucial for planning appropriate safety measures. Occupational health and safety legislation requires organizers to conduct a risk assessment to prevent workplace injuries, occupational diseases, work-related illnesses, and disruptions to work processes. Injuries to staff (e.g., coaches, support personnel, security guards), participants, and spectators can occur at sports events; therefore, prevention is a priority.

Consequently, measures to reduce and eliminate risks at sports competitions must include: systematic risk assessment by job role and activity; preventive technical and organizational measures (e.g., safety barriers, access control, staff training); and clearly defined procedures for accidents or evacuations [8].

4.1. Responsibilities of sports event organizers

The Occupational Safety and Health Act and regulations adopted pursuant to that Act stipulate the employer's obligations in implementing occupational safety. The employer is obliged to organize and implement occupational safety, taking into account risk prevention, worker notification, worker training, work organization and work equipment. Occupational safety is part of the organization

of work and the performance of work procedures. Among the most important obligations of the employer arising from the provisions of the Occupational Safety and Health Act is risk assessment. Based on the risk assessment, preventive measures are implemented and workers are trained to work safely. Workers are trained to work safely according to the risk assessment and must include all hazards, hazards or efforts identified in the risk assessment and methods of elimination. The organizer of a sports event plays a key role in implementing occupational safety, because in addition to its employees, it is also responsible for all persons involved in the event: competitors, coaches, volunteers, medical teams and spectators. The organizer must also ensure safe infrastructure and competition areas, an evacuation plan and emergency measures, an adequate number of security guards, stewards and volunteers, medical services and first aid, and training of personnel for responding to crisis situations.

The organizer is also responsible for regular maintenance of equipment and competition areas and for conducting internal safety checks before and during the competition. For all major events, it is recommended to form a special safety committee to coordinate all activities related to occupational safety and the safety of participants [9].

4.2. Role of technical and support staff

The technical staff is responsible for the preparation and maintenance of all sports facilities, equipment and infrastructure required for the competition. It carries out the installation and maintenance of technical systems, including audiovisual equipment, electrical installations, lighting, protective nets and other equipment that ensure the smooth running of the event. The technical staff also coordinates activities with other sectors of the organization, including security services, medical support and administrative staff, to ensure the full safety and functionality of the event. During the competition, the technical staff provides constant technical support and resolves any malfunctions or problems in real time, which is essential for the smooth running of the competition and the protection of participants and spectators.

Support staff includes volunteers, stewards, administrative staff and others who support the organization of the event with various tasks. Their responsibilities include administrative support, such as managing registrations, schedules and communication with participants and spectators. Support staff monitors access to certain parts of the event, ensures that only authorized persons have access and helps maintain order. They also provide information, direct participants and spectators and help resolve any problems or accidents. In this way, support staff ensures that all event participants and visitors have a safe and organized experience.

Together, technical and support staff form the key framework for organizing sports competitions. While technical staff ensure that infrastructure and equipment operate according to safety standards, support staff oversee and coordinate participants and the audience, thereby helping to reduce risk and enhance the event's overall safety. Their coordination and cooperation with organizers and other services constitute the foundation for the successful and safe execution of sports events [10].

4.3. The importance of education and training of participants and workers

Education and training of participants and workers in the organization of sports events plays a key role in ensuring the safety, efficiency and successful implementation of competitions. The main objectives of education include improving the skills and knowledge of all participants, increasing safety through knowledge of protocols and procedures, and improving communication and coordination between all teams involved. Participants and workers who are adequately educated

and trained are better prepared to recognize potential hazards in a timely manner, prevent accidents and react in crisis situations. Education includes theoretical classes, where basic concepts, rules and safety protocols are covered, practical exercises that simulate real situations and allow the application of what has been learned in controlled conditions, and workshops and interactive trainings that encourage active participation and problem solving in groups. Such a combination of methods ensures that participants and workers not only understand the procedures but also apply them effectively in the real context of a sports event. Continuous education is of particular importance, which allows for constant updating of knowledge, monitoring of new technologies and legislative changes, and preparation of participants for unforeseen situations. Regular training also strengthens team spirit and trust among participants, which contributes to better coordination and efficiency during the event. Evaluating the program and collecting feedback from participants allows for the identification of areas for improvement and adjustment of future programs, thereby continuously raising the quality of training. All these activities together ensure that sporting events are organized in a professional and safe manner, reducing the risk of injuries and ensuring a positive experience for all participants and spectators.

Athletes and recreational athletes need to know the rules of the sport, the technique of performing movements, and basic safety measures, such as warming up and using protective equipment. It is also important to be informed about potential risks, such as slippery surfaces or improperly installed equipment, and to have basic first aid knowledge.

Recommended training measures:

- workshops and practical exercises, such as emergency simulations and the use of protective equipment
- online courses and certificates, useful for training a larger number of participants and volunteers
- regular refresher courses, so that information is not forgotten and everyone remains prepared for unexpected situations [11].

4.4. The role of volunteers and participants in maintaining safety

Volunteers and participants play a key role in maintaining safety at sporting events. Volunteers are responsible for monitoring and controlling the area, directing spectators, and cooperating with professional security services. Their activity ensures that all attendees respect safety protocols, and by reacting in a timely manner they can prevent accidents and reduce the risk of injuries. Proper education and training of volunteers is crucial for the successful implementation of their tasks. Volunteers must be familiar with evacuation plans, safety protocols, and methods of communication in crisis situations. Training ensures that volunteers can react quickly and effectively, and coordinate their activities with other teams and services during the event.

Volunteer Responsibilities:

- Space and Equipment Control: Volunteers ensure that sports surfaces are safe, equipment is functioning properly, and that walkways and exits are clear
- Instructions to participants and the audience: Providing information about safety rules, marked routes, evacuations, and first aid points
- Rapid response in emergency situations: Trained volunteers can respond promptly in the event of an injury, crowd, or other crisis

Participants, including athletes, coaches, and staff, also play an important role in maintaining safety. Their responsibilities include following rules and procedures, using equipment properly, and reporting potential hazards in a timely manner. Active participation by participants contributes to the effectiveness of safety measures and reduces the likelihood of accidents. Coordination and communication between volunteers and participants is essential for timely identification and resolution of safety threats. Cooperation between both parties strengthens team cohesion and ensures that all participants contribute together to the professional, safe, and efficiently organized implementation of sports events.

Participant Responsibilities:

- Adherence to rules and instructions: following the rules of the sport, using protective equipment, and listening to instructions from staff and volunteers
- Hazard Reporting: actively noticing potentially dangerous situations, such as faulty equipment or slippery surfaces, and notifying the appropriate authorities
- Crisis Response: Participants should know basic first aid and evacuation procedures to help themselves and others [9].

5. CONCLUSION

Sports and sports competitions are complex events that require quality planning and organization to ensure the safety of all participants. Risk assessment forms the basis of occupational safety and is a key element of the safety of sports events. The Occupational Safety and Health Act emphasizes the obligation to identify and analyze potential hazards and define preventive measures to reduce the possibility of injuries or accidents. In the context of sports competitions, risk assessment encompasses physical, technical and organizational hazards, including the safety of athletes, spectators, staff and volunteers. Systematic risk assessment allows organizers to plan safety protocols and react in a timely manner in unforeseen situations.

Active involvement of all participants in risk identification, planning and problem solving contributes to the reduction of accidents and ensures a better experience for all participants. Timely communication, compliance with protocols and continuous training of staff are key elements that guarantee the safety and success of the organization of sports events.

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Professional paper

REGISTRY DATA ON WORKERS EXPOSED TO BIOLOGICAL AGENTS IN THE REPUBLIC OF CROATIA

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Abstract: *The minimum requirements for the protection of workers' safety and health from risks arising, or likely to arise, from exposure to biological agents at work are laid down in the Ordinance on the Protection of Workers from Risks Due to Exposure to Biological Agents at Work. In accordance with this Ordinance and the Health Care Act, all employers in the Republic of Croatia are required to report aggregate data on workers who are exposed, or may be exposed to biological agents at work to the Department of Occupational Health of the Croatian Institute of Public Health (CIPH). Data have been collected since 2015 and are presented in this paper.*

Keywords: *exposed workers, biological agents, occupational exposure*

1. INTRODUCTION

Biological agents are ubiquitous in the environment and are present across a wide range of occupational sectors. Because they are often invisible, the risks they pose may be underestimated. However, exposure can result in acute and chronic diseases, some of which may be life-threatening and have serious socioeconomic consequences. Adverse health effects include infections, zoonotic diseases, upper and lower respiratory tract disorders, occupational asthma, sensitization, allergic reactions, systemic (multi-organ) effects, poisoning, and cancer [1].

Biological agents include microorganisms (also genetically modified microorganisms), cell cultures, and human endoparasites that may cause infection, allergy or toxicity. According to their level of risk of infection biological agents are classified into four risk groups [2]:

- group 1 biological agent means one that is unlikely to cause human disease:
- group 2 biological agent means one that can cause human disease and might be a hazard to workers; it is unlikely to spread to the community; there is usually effective prophylaxis or treatment available;
- group 3 biological agent means one that can cause severe human disease and present a serious hazard to workers; it may present a risk of spreading to the community, but there is usually effective prophylaxis or treatment available;

- group 4 biological agent means one that causes severe human disease and is a serious hazard to workers; it may present a high risk of spreading to the community; there is usually no effective prophylaxis or treatment available [2].

Although biological hazards occur across many sectors, occupational exposure is concentrated in several high-risk sectors (Table 1).

Table 1: Occupational risk to biological agents of exposed workers

National Classification of Activities, ver. 2025.	Exposed workers	Risk
Human health	Physicians, nurses, laboratory technicians	High risk of exposure to airborne and bloodborne pathogens
Veterinary activities	Veterinarians and animal health workers	Exposure to zoonotic diseases
Agriculture, forestry and fishing	Outdoor workers and workers in contact with animal	Exposure to moulds, spores, and tick-borne diseases.
Water supply; sewerage, waste management and remediation activities	Sanitation workers, waste management personnel, and wastewater treatment plant workers	Exposure to bioaerosols, bacteria, and decomposing organic matter.

2. LEGAL AND REGULATORY FRAMEWORK

The Ordinance on the Protection of Workers from Risks Due to Exposure to Biological Agents at Work establishes the minimum requirements for the protection of workers' health and safety from risks arising from occupational exposure to biological agents. The Ordinance transposes Directive 2000/54/EC of the European Parliament and of the Council on the protection of workers from risks related to exposure to biological agents at work into Croatian legislation [3].

In accordance with the Ordinance and the Health Care Act [4], employers are required to report workers who are exposed, or may be exposed, to biological agents at work to the Department of Occupational Health of the CIPH. For activities involving biological agents classified in risk groups 2, 3, or 4, employers must notify the Department of Occupational Health of the CIPH at least 30 days before commencing work.

The following information must be submitted:

- the first use of each Group 2, 3, or 4 biological agent;
- each newly identified Group 3 biological agent temporarily classified by the employer;
- information on the occupational safety professional responsible for workplace safety;
- findings from the risk assessment, including the nature, degree, and duration of exposure;
- the type of biological agent involved; and
- the preventive and protective measures implemented.

Employers are also required to report any accident or incident involving biological agents that could result in their release and potentially cause infection or disease in humans. Furthermore, records of exposure to Group 3 and Group 4 biological agents must be retained for at least 10 years after the end of exposure and, in specific cases involving long-latency diseases, for up to 40 years [3].

3. METHODOLOGY

To facilitate compliance with reporting obligations, the Department of Occupational Health of the CIPH created a registration form for workers exposed to biological agents at work and has maintained a registry since 2015. The study is based on a descriptive analysis of registry data collected between 2015. and 2025. Currently, the registry contains data from only seven employers.

Employers complete the form using information obtained through workplace risk assessments. These assessments identify biological agents present in the workplace, determine the nature, degree, and duration of occupational exposure, assess the associated risks, and specify preventive measures intended to protect workers' health. The reporting form allows employers to record exposure to up to three biological agents per worker, with additional entries possible where necessary. Data collected include information on the employer, occupational sector, exposed workers, biological agents involved, and risk assessment findings. Since the establishment of the registry, a total of 403 workers employed by seven employers have been registered.

4. DISCUSSION

In EU (29 European countries and 50 organisations), a global overview of sectors where occupational exposure to biological agents may occur is presented in the EU-OSHA report „*Biological agents and work-related diseases: results of a literature review, expert survey and analysis of monitoring systems*“. In these report a main biological agents of concern are:

- in health care and hospitals: infectious agents including viruses (e.g. Hepatitis, human immunodeficiency viruses, rubella, Rabies, influenza, Severe acute respiratory syndrome-related coronavirus (SARS-virus)), bacteria (e.g. Staphylococcus aureus, Streptococcus pyogenes, Mycobacterium tuberculosis, Legionella, Clostridium), fungi (e.g. Tinea spp, Aspergillus spp), parasites (e.g. Giardia lamblia) and prions
- in laboratories: infectious agents including zoonotic agents (e.g. Trichophyron spp, Toxoplasma gondii, Rabies), parasites (e.g. Leismania spp) and prions. Allergens (e.g. from mites, plant material and animal proteins from urine, hair and skin)
- in Waste collection, treatment and sorting: fungi (e.g. Aspergillus fumigatus, and yeasts), infectious (e.g. Salmonella) and non-infectious bacteria (e.g. E. Coli, actinomycetes). Endotoxins, glucans, and viruses (e.g. Hepatitis A, Hepatitis B)

Analysis of the collected reports in Croatia show that occupational exposure to biological agents is most frequently reported in healthcare services, wastewater treatment facilities, waste disposal facilities and clinical, veterinary, and diagnostic laboratories (Table 2).

Table 2: Most frequently reported biological agents according to occupational activity

INDICATIVE LIST OF ACTIVITIES (Ordinance - ANNEX I)	Number of exposed workers	Biological agens
Healthcare activities, including isolation and post-mortem units	219	Mycrobacterium tuberculosis, HCV, HBV, HIV, SARS-CoV-2
Wastewater treatment facilities	123	HBV, HCV, Salmonella typhi, E. coli, Salmonella, Shigella, Staphylococcus), Leptospira interrogans, Clostridium tetani, Fungi that can cause alergy
Waste disposal facilities	49	HBV, HCV, Salmonella typhi, E. coli, Salmonella, Shigella, Staphylococcus epidermidis, Leptospira interrogans, Clostridium tetani, Fungi that can cause allergy
Clinical, veterinary, and diagnostic laboratories	12	Clostridium sporogenes ATCC 11437, E. coli W3110 (In House microorganism), Staphylococcus epidermidis (In House microorganism), Corynebacteria (In House microorganism), Candida ablicans ATCC 10231, Aspergillus brasiliensis ATCC 16404, Staphylococcus aureus ATCC 6538, Pseudomonas aeruginosa ATCC 9027

The majority of reported exposures involve biological agents classified in risk groups 2 and 3. Healthcare workers account for the largest proportion of registered workers, with exposure primarily related to Mycobacterium tuberculosis, hepatitis B and C viruses, human immunodeficiency virus and SARS-CoV-2. Workers employed in wastewater treatment and waste management facilities are commonly exposed to enteric bacteria, Leptospira interrogans, Clostridium tetani, and allergenic fungi.

Although biological hazards are present in numerous occupational sectors, only 403 workers employed by seven employers have been reported over a ten-year period. This figure appears disproportionately low when compared with the number of workers potentially exposed in healthcare, agriculture, waste management, food production, veterinary services, research laboratories, and other sectors.

The low number of registered workers may indicate underreporting, insufficient awareness of reporting obligations, inadequate workplace risk assessments or a combination of these factors. Furthermore, there is limited information regarding the extent to which employers maintain internal records of occupational exposure to biological agents.

The collected data nevertheless provide valuable insight into occupational exposure patterns in Croatia and may support the development of targeted preventive measures, educational activities and occupational health policies.

5. CONCLUSION

Biological agents represent an important occupational hazard in a wide range of sectors. Croatian legislation requires employers to assess and report occupational exposure to biological agents and to maintain records of exposed workers. Since 2015, the CIPH has maintained a registry of reported exposures.

Despite the widespread presence of biological hazards in the workplace, only 403 workers have been registered over the past decade. This suggests substantial underreporting and highlights the need to improve employer awareness, strengthen compliance with reporting obligations, and enhance the quality of workplace risk assessments.

More comprehensive reporting would provide a better understanding of occupational exposure to biological agents in Croatia and support the development of effective prevention and worker protection strategies.

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Professional paper

ACTIVE BREAK AT THE WORKPLACE – AN EXERCISE PROGRAMME FOR OFFICE WORKERS

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Abstract: *Sedentary office work is one of the most prevalent risk factors for musculoskeletal disorders (MSD). Prolonged static sitting induces muscular imbalance, fascial stiffness, impaired capillary perfusion, and the accumulation of algogenic metabolites, leading to pain in the cervical, shoulder, and lumbar regions. The prevalence of MSD among office workers exceeds 80%, with substantial individual, economic, and societal consequences. From a physiotherapy perspective, active breaks – short bouts of light exercise performed every 20–30 minutes of sitting – represent an evidence-based preventive strategy.*

A combined programme of targeted stretching and strengthening exercises addresses the underlying muscular imbalances rather than merely relieving symptoms. Regular active breaks reduce MSD symptoms, improve posture, decrease perceived stress, and do not diminish work productivity. Physiotherapist-supervised implementation yields superior outcomes and is recommended as the standard of care for workplace health promotion.

Keywords: *active break, office work, stretching exercises, strengthening exercises, musculoskeletal disorders*

1. INTRODUCTION

Office work has become the predominant form of employment in the developed world over recent decades. According to World Health Organization data, more than 60% of the working-age population in high-income countries performs sedentary or predominantly sedentary work. Despite advances in ergonomics and growing awareness, physical inactivity during working hours remains seriously neglected in most office settings. The consequences manifest at the individual level as pain, reduced mobility, and poorer quality of life, as well as at the employer and healthcare system levels [1]. Physiotherapists encounter increasingly frequent patients whose symptoms – chronic neck and shoulder pain, lumbar tension, restricted range of motion throughout the body, and general fatigue – arise directly from sedentary work patterns. These are musculoskeletal disorders (MSD), among the most common occupational diseases in the developed world. The clinical presentation of

an office worker manifests as pain in the neck or lower back, resulting from the tension of shortened muscles and the weakness of inhibited muscles, along with consequent postural compensations that over time lead to degenerative changes in musculoskeletal structures.

Office posture is frequently described within the framework of Janda's concept of the "Upper Crossed Syndrome" (UCS) and "Lower Crossed Syndrome" (LCS). Both describe a specific pattern of muscular imbalance that arises as a consequence of prolonged maintenance of a static posture [2]. The Upper Crossed Syndrome (UCS) describes a pattern in which the upper trapezius, levator scapulae, pectoralis major and minor, and sternocleidomastoideus are shortened, while the deep neck flexors (longus colli, longus capitis), rhomboids, and lower trapezius are weakened. The consequence is the typical office worker posture characterised by increased cervical lordosis, forward head position, increased thoracic kyphosis, and shoulder protraction. The prevalence of UCS among office workers ranges between 28 and 67% [2]. The Lower Crossed Syndrome (LCS) describes an analogous imbalance in the pelvic and hip region, in which the hip flexors (iliopsoas, rectus femoris) and back extensors are shortened, while the abdominal and gluteal muscles are weakened. The result is anterior pelvic tilt, increased lumbar lordosis, and compensatory hyperextension of the lumbar spine – one of the primary biomechanical causes of chronic low back pain in sedentary workers [2].

A recent cross-sectional study reported an 80.8% prevalence of MSD, with the cervical region affected in 58.6%, the lumbar region in 52.5%, and the shoulders in 37.4% of participants [3]. MSD also represent a major challenge for healthcare systems, as evidenced by data showing that in the United Kingdom in 2021–2022 they accounted for 27% of all occupational diseases and caused 6.6 million lost working days [4]. The most prevalent postural disorder among office workers is Forward Head Posture (FHP). Its global prevalence exceeds 66% [5]. Biomechanical analysis indicates that each centimetre of forward head displacement from the vertical spinal axis increases the load on the cervical segments by approximately 4–5 kg. At 60° of cervical flexion, this amounts to up to 27 kg [6].

The economic burden of MSD is immense. It is estimated that MSD in EU countries cause annual costs amounting to 0.5–2% of GDP, including treatment costs, lost working days, and reduced productivity. Presenteeism – attending work despite pain and diminished work capacity – is more prevalent among office workers with MSD than absenteeism and represents a hidden yet economically significant cost for employers [7].

A major risk factor for the development of MSD is prolonged sedentary work involving various static postures. To prevent this condition or reduce pain intensity where already present, ergonomic workstation adjustment is necessary, though insufficient on its own [7]. It must be combined with the regular performance of specific exercises, as only through this combined approach can optimal outcomes be achieved. It is therefore recommended that active breaks be incorporated into the working day to reduce the adverse effects of static posture.

2. CAUSES OF PAIN

Prolonged static loading is a well-established mechanism of pain development in physiotherapy. During sitting, particularly in the typical office posture, various changes occur that lead to systemic disturbances.Static muscle contractions impair capillary blood flow, leading to the accumulation of metabolic waste products. When a muscle exceeds 15–20% of its maximum voluntary contraction (MVC) in a static position, perfusion is reduced, resulting in tissue hypoxia and the accumulation of

lactic acid and algogenic substances – the direct chemical cause of pain. Algogenic metabolites are substances produced in muscle tissue during work. When blood flow is normal, they are continuously cleared from the tissue. When flow is impaired due to prolonged static muscular loading, these substances accumulate in the muscle tissue and cause pain. These metabolites include lactate (lactic acid), which lowers local pH and activates pain receptors; bradykinin, which directly activates nociceptors and produces a dull, diffuse muscular pain; and prostaglandins, inflammatory mediators produced under prolonged loading, which sensitise nerve endings and lower the pain threshold – forming the basis for hypersensitivity in chronic pain states.

The mechanism of reduced blood flow under low-level static loading is well documented in the kinesiological literature [1]. When a muscle sustains a static contraction above the 15–20% MVC threshold, intramuscular pressure exceeds capillary perfusion pressure and induces functional tissue ischaemia. This condition is particularly critical for the muscles of the upper shoulder girdle (trapezius, levator scapulae), which during typing and mouse work frequently sustain low but continuous activation that workers often do not even perceive as muscular effort. This is precisely why short active breaks are so effective – every muscular contraction and relaxation during movement mechanically expels these metabolites from the tissue and restores capillary flow. Intense exercise is not required; light activity that re-establishes normal circulation is sufficient.

In addition to muscle tissue, fascial tissue is particularly sensitive to immobility. The fascia is a dense connective tissue network that envelops and interconnects muscles, organs, and nervous structures throughout the body. With prolonged immobility, collagen fibres undergo reorganisation into less elastic, cross-linked patterns, and the viscosity of hyaluronan – the molecule responsible for interfascial gliding – increases. The result is increased stiffness and reduced interfascial gliding capacity, which clinically manifests as pain upon initial movement after prolonged rest and a subjective sensation of stiffness and bodily rigidity [8].

3. ACTIVE BREAK

An active break (active microbreak) is a short, intentional interruption of sedentary work with movement. [3] define it as 2–3 minute breaks incorporating light physical activity every 30 minutes of seated work. It may also be performed in a longer format lasting 10–15 minutes, performed once daily. In both formats, it is essential that the exercises do not cause pain. Two principal forms of active break appear in the literature. Short microbreaks of 2–3 minutes every 20–30 minutes are intended to prevent the accumulation of muscular tension and metabolic waste products. Longer group sessions of 10–15 minutes once daily are better suited for the systematic management of muscular imbalance through exercise and have greater potential for long-term postural changes. A combined approach – short microbreaks together with longer exercise units – achieves substantially greater reductions in musculoskeletal discomfort than either format alone [10].

The performance of active breaks stimulates several physiological mechanisms. A brief muscular contraction or stretch immediately restores local blood flow in previously hypoxic tissue, clearing metabolites and re-establishing oxygenation. Muscular contraction also activates mechanoreceptors. Muscle spindles and Golgi tendon organs reduce central sensitisation and nociceptor excitability, producing the analgesic effect of exercise. Rhythmic stretching and fascial tissue compression during movement drive fluid through the tissue and maintain collagen hydration, thereby reducing

fascial stiffness. Correctly designed strengthening exercises during the break activate the deep trunk stabilisers and cervical flexors, which are inhibited during prolonged sitting, thereby improving overall postural alignment [7].

Workplace exercise has proven effective in reducing pain in the cervical, shoulder, and lumbar regions of office workers [11]. Combined approaches incorporating both stretching and strengthening exercises have demonstrated the greatest effectiveness. Professional supervision and guidance by a physiotherapist is an important contributing factor [7, 12]. Active breaks of 2–3 minutes every 30 minutes of sitting have the potential to reduce musculoskeletal discomfort, improve metabolic parameters, and decrease fatigue without adverse effects on productivity [9]. Both active and passive breaks reduce the presence and intensity of MSD, with active breaks demonstrating superior outcomes on musculoskeletal symptomatology [4].

3.1. Physiotherapy recommendations for exercise

The physiotherapeutic approach to exercise in office workers is based on biomechanical assessment and identification of shortened and weakened tissues, upon which a targeted exercise programme is subsequently designed. The exercise programme should include both strengthening and stretching exercises. Strengthening addresses the underlying causes of muscular imbalance, while stretching reduces stiffness and pain symptomatology [7]. Strengthening exercises should also incorporate activation of the deep trunk and cervical stabilisers, which are frequently inhibited during sedentary work. Their activation is the foundation of functional recovery [13]. The principle of specificity is important in exercise selection – exercises should target the muscle groups functionally engaged in office work: the neck, shoulder girdle, trunk, and hips. General aerobic exercise is beneficial but does not substitute a specific programme. Progressive overload is appropriate, meaning that strengthening exercises begin with bodyweight only, with loading subsequently increased through the use of resistance bands or light free weights. It is essential to account for individual differences among participants, including age, physical fitness, the presence of acute pain, previous injuries, and the severity of MSD. Only by doing so can safe and sustainable progress be ensured [14].

3.2 Active break poster

The exercise complex presented here was developed on the basis of a review of professional and scientific literature in physiotherapy, kinesiology, and ergonomics. The complex is divided into two parts: the larger portion comprises stretching exercises, while the second part consists of strengthening exercises. Each exercise is illustrated with an image, accompanied by a brief description of the movement and starting position. The stretching exercises target the muscles most heavily loaded or shortened in the typical office posture – the muscles of the neck, chest, wrist, back, pelvic girdle, and legs. The strengthening exercises aim to activate muscles that are held in an elongated, weakened position during office work. These include the cervical flexors, periscapular muscles, gluteal muscles, and leg muscles. Figure 1 presents the Active Break poster, which also specifies the recommended number of repetitions or stretching duration for each exercise and the number of sets.



Figure 1: Active break poster

4. IMPLEMENTATION OF ACTIVE BREAKS IN THE WORK PROCESS

The success of workplace exercise programmes depends on professional supervision [7, 10]. The physiotherapist plays a central role in implementing an active break programme: conducting an initial assessment of workers for the presence of MSD, postural deviations, and possible contraindications. Following assessment, the exercise programme is planned according to the identified MSD and individualised to participant needs. Workers are then educated through explanation, demonstration, and correction of all exercises as required. The programme should begin with lighter exercises, with progression applied throughout. Joint range of motion measurements, functional tests, and validated questionnaires should be administered before and after the completed programme. The results reflect the impact of exercise on the individual's overall health status and serve as motivation for continued engagement.

For the assessment of programme effectiveness, the use of validated measurement instruments is recommended to evaluate the presence and intensity of musculoskeletal discomfort and perceived stress before and after the intervention [15]. In addition to questionnaires, the physiotherapist should perform functional tests measuring the range of motion of the cervical and thoracic spine, as well as tests of gluteal and trunk core strength. Successful implementation requires management support to ensure that active breaks are incorporated into the work schedule. When active breaks are performed as group exercise, this increases adherence and simultaneously fosters a positive workplace culture. For regular engagement, the introduction of digital reminders to prompt workers towards activity is advisable.

5. CONCLUSION

Musculoskeletal disorders in office workers are not inevitable. They are a predictable consequence of biomechanically unfavourable work patterns. Contemporary clinical literature unequivocally confirms that regular active breaks reduce MSD symptoms, improve posture, reduce stress, and do not diminish productivity. Primary prevention of MSD in office workers is substantially less costly than treating established occupational diseases. The physiotherapist, as a specialist in movement and musculoskeletal health, holds a pivotal and unique role in the design of preventive programmes in the workplace – a role that extends beyond the clinical treatment of individual patients.

From a physiotherapy perspective, it is essential that active breaks include not only stretching exercises, but also targeted strengthening of weakened muscle groups – particularly the deep trunk stabilisers and cervical flexors. Only in this way do we address the underlying causes of muscular imbalance rather than merely alleviating symptoms. The physiotherapist fulfils an indispensable role throughout the implementation process: from initial biomechanical assessment of workers and design of an individualised programme, to training, supervision of execution, and outcome evaluation. Programmes delivered under physiotherapeutic supervision have the potential to achieve superior outcomes compared to self-directed programmes without professional oversight.

An active break is an investment – in worker health, in the reduction of absenteeism, and in the long-term sustainability of the workforce. Every employer who integrates a professionally designed active break programme into their organisational culture stands to gain measurable health and economic benefits.

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Original scientific paper

SAFETY ANALYSIS OF WORKING MACHINE CABS USING EXPERIMENTAL AND NUMERICAL METHODS

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Abstract: *Working machines used in construction, agriculture, and industry are exposed to various hazards during operation, such as machine rollover or falling objects onto the operator's workspace. The cab structure represents a key component of operator protection and one of the fundamental requirements of occupational safety systems. This paper analyzes the safety of the working machine cab structure through experimental and numerical investigations. Special emphasis is placed on the application of ROPS (Rollover Protective Structures) and FOPS (Falling Objects Protective Structures) methods. In addition to experimental tests, a numerical analysis of the stress–strain state of the structure was performed using the finite element method (FEM). The results demonstrate that the combination of experimental and numerical methods enables a reliable assessment of the cab structure's safety and contributes to improving operator safety.*

Keywords: *Safety at work, Working machines, Operator cab, ROPS, FOPS, Numerical analysis*

1. INTRODUCTION

Working machines play a key role in modern construction, agriculture, and industrial production; however, their use also represents a potential hazard to operators [1,2]. To increase operator safety, protective structures for machine cabs have been developed to preserve the operator's safety space in accordance with the requirements of international machine safety standards [3,4]. Of particular importance are tests of cab protective structures using the ROPS (Rollover Protective Structure) method according to the EN ISO 3471 standard and the FOPS (Falling Object Protective Structure) method according to the ISO 3449 standard, which simulate typical accident scenarios during the operation of working machines [5,6].

ROPS tests simulate machine overturning and enable the assessment of the cab structure's resistance to static loads, while FOPS tests simulate the impact of falling objects on the cab roof and assess its resistance to dynamic loads [4,7]. During these tests, special attention is given to the so-called DLV (Deflection Limiting Volume), i.e., the operator's safety space inside the cab that must remain preserved after structural deformation [1,7].

Although numerous studies have addressed ROPS and FOPS protective structures, relatively few published studies combine experimental testing with numerical analysis of working machine cabs. In this paper, the cab design of a TH 3.6 telescopic loader model is analyzed from the perspective of operator safety using both experimental and numerical methods. The paper aims to assess the safety of the cab design and its contribution to operator protection under working conditions.

2. SUBJECT AND METHODS OF ANALYSIS

2.1. Subject of Analysis

The cab of the Telehandler TH 3.6 telescopic loader, shown in Figure 1, is used in the construction and agricultural industries. The cab structure consists of a steel frame made of profile elements connected by welded joints. Other cab components are made of glass and composite materials, ensuring good visibility and a reduction in the overall structural mass. The cab is mounted to the machine chassis using elastic supports, which reduce vibration transmission and contribute to improved operator working conditions.



Figure 1: Cab structure of the TH 3.6 telescopic loader model

The load-bearing structure of the cab is made of structural steel S235 J2 due to its good weldability and favorable mechanical properties. The structural components are interconnected by welding. The basic mechanical properties of S235 J2 steel are presented in Table 1.

Table 1: Basic mechanical properties of S235 J2 steel

Property	Value
Yield strength (R_e)	235 MPa
Tensile strength (R_m)	360 - 510 MPa
Impact energy (W)	27 J
Elongation (A)	22 - 26 %

The operator's safety space (DLV) in telescopic loaders, including the TH 3.6 model, is defined by the ISO 3164 standard as a geometrically standardized volume with approximate dimensions of 680 mm in width, 1000 mm in height, and 800 mm in length, positioned relative to the seat reference point.

2.2. Methods Used for Analysis

Three analysis methods were used in this study: the FOPS test, the ROPS test, and the FEM method.

The FOPS test simulates the fall of objects onto the roof of a working machine cab using a weight of defined mass and drop height. There are two testing levels: FOPS Level I – lower loads (fall of a lighter object), and FOPS Level II – higher loads (fall of a heavier object). The first weight is dropped onto the area above the operator's legs, i.e., the front part of the cab structure. The second weight is dropped onto the area above the operator's head at the rear part of the structure.

The ROPS test simulates machine rollover by applying lateral, vertical, and longitudinal loads to the cab structure. The objective of the test is to verify that the structure can absorb rollover energy without compromising the operator's safety space.

The numerical analysis was performed assuming linear-elastic material behaviour; therefore, local plastic deformation effects were not considered in the model. Contact was modeled as frictionless, and supports were assumed to be rigid [2,7,8]. The impact was approximated quasi-statically, with energy input based on free-fall energy according to ISO 3449 [5].

3. EXPERIMENTAL AND NUMERICAL PRESENTATION OF TESTING

After preparing the cab structure (Figure 2), FOPS testing of the first and second levels (DLV legs and DLV head) was performed, with the resulting deformations shown in Figures 3 and 4.

ROPS tests verify the cab structure's resistance to static loads, as shown in Figure 5 for lateral loading, Figure 6 for vertical loading, and Figure 7 for longitudinal loading.



Figure 2: Preparation for FOPS testing

FOPS Level I
Spherical shape
Mass: 45 kg
Developed energy: 1365 J





Figure 3: Cab roof deformation – first impact

FOPS Level II
Cylindrical shape
Mass: 227 kg
Developed energy: 11600 J





Figure 4: Cab roof deformation – second impact



Figure 5: Cab deformation under lateral loading



Figure 6: Cab deformation under vertical loading



Figure 7: Cab deformation under longitudinal loading

Experimental testing yielded positive results, as no part of the cab structure, after deformation, entered the operator's protective zone (DLV – width ~680 mm, height ~1000 mm, and length ~0.8 m, positioned relative to the seat reference point) in accordance with ISO 3164.

In addition to the experimental testing, a numerical analysis of the cab structure was also performed using the finite element method (FEM). The numerical analysis was carried out in INVENTOR software using 3D solid elements with an average mesh size of 10 mm, after which boundary conditions and loads corresponding to the FOPS and ROPS tests were defined. Stress distribution and deformation distribution within the structure were analyzed.

By applying the load of the first impact to the structure according to the previously defined values, results were obtained for the distribution of Von Mises stresses within the material (Figure 8) and maximum deformations (Figure 9).

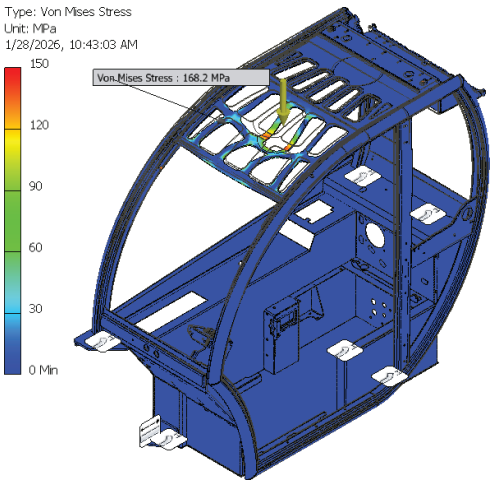


Figure 8: Von Mises stress distribution – first impact

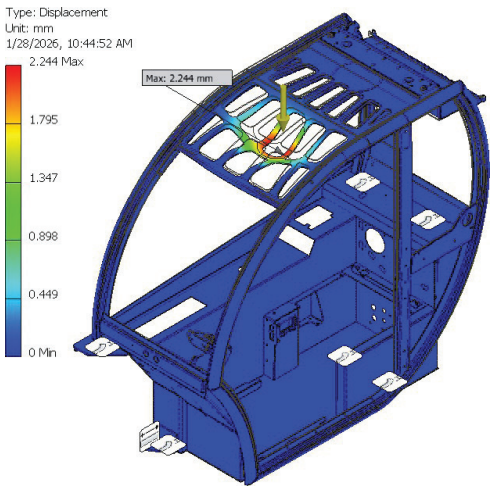


Figure 9: Deformation distribution – first impact

The distribution of Von Mises stresses for the first impact shows that the maximum load occurs at the point of impact, with a stress value of 168.2 MPa. The maximum deformation of the structure also occurs in the same zone, with a value of 2.24 mm.

The analysis of the second impact indicates significantly higher stress levels, with the maximum value reaching 427 MPa. This stress value indicates a local exceedance of the material's yield strength (R_e = 235 MPa). Although local stress values exceeded the nominal yield strength of the

material, the deformation remained localized and did not compromise the integrity of the operator's safety space (DLV), which represents the primary acceptance criterion according to ISO 3449.

The maximum deformation of the roof structure during the second impact occurs in the contact zone of the weight and amounts to 9.773 mm, confirming that the highest stresses and deformations are concentrated in the area of direct load application.

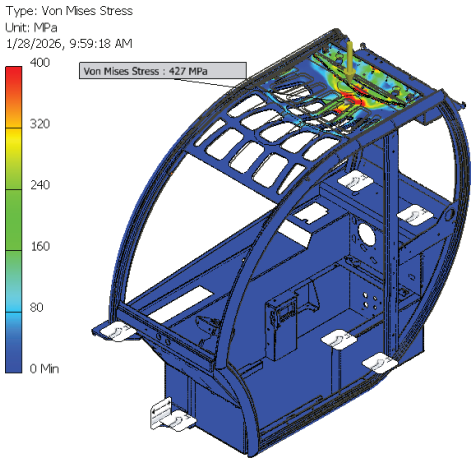


Figure 10: Von Mises stress distribution – second impact

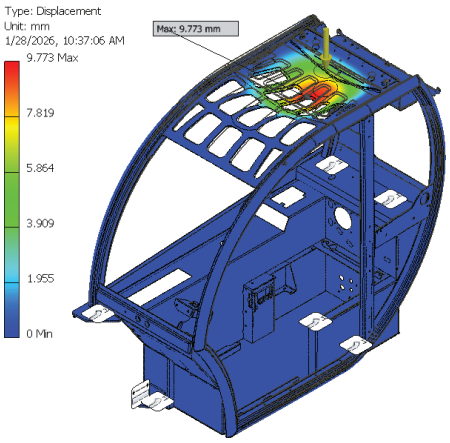


Figure 11: Deformation distribution – second impact

The results of the numerical analysis show that the cab structure of the TH 3.6 telescopic loader can withstand the loads prescribed by the standards, without any deformation entering the operator's safety space (DLV – width ~680 mm, height ~1000 mm, and length ~0.8 m, positioned relative to the seat reference point) in accordance with ISO 3164.

The deformation values remain within acceptable limits, confirming the adequacy of the structural design. Furthermore, the results indicate good agreement between numerical and experimental testing, thereby validating the FEM model of the cab with respect to the FOPS tests.

4. CONCLUSION

The results of experimental and numerical analyses indicate that the cab structure meets the safety requirements defined by international standards. During the FOPS and ROPS tests, structural deformations did not compromise the operator's safety space (DLV), confirming the adequacy of the structural design.

The obtained numerical results show good agreement with the experimental findings, thereby confirming the reliability of the finite element method for assessing the safety of cab structures. The observed deviations are relatively small (within a few percent) and can be attributed to simplifications in the numerical model, such as linear-elastic material behaviour and idealisation of contact conditions. Nevertheless, the model successfully reproduced stress and deformation distributions, as well as critical load zones, further confirming the applicability of the FEM approach in the early stages of design.

The obtained results are consistent with previous studies on ROPS/FOPS protective structures, which confirm that properly designed cabs significantly reduce the risk of injury.

The combination of experimental testing and numerical simulations enables a reliable assessment of cab structural resistance and can be effectively applied in the design phase to improve operator safety and optimise the structure. Future research may focus on improving numerical models by incorporating nonlinear material behaviour and more detailed contact modelling, as well as validation on a larger number of experimental cases, which would further reduce deviations and increase simulation accuracy.

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Original scientific paper

CHECKING THE SAFETY AND OPERATIONAL CONDITIONS OF WORK EQUIPMENT IN INTERACTIVE MODULES

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Abstract: *This study presents the technical design of an interactive digital checklist for the pre-operational inspection of a Manitou MT 1335 telehandler used with a work platform for personnel lifting. Rather than centring on a specific software product, it defines the contents, functional organization and operational requirements such a checklist should incorporate, and configures and tests them on a digital inspection platform. Methodologically, the work is an applied, design-oriented study based on documentary analysis of sources provided by the company — the paper checklist currently in use, the Manitou MT-series operator manual, a critical-points brochure for the telescopic boom and work platform, and internal maintenance records for 2025 — read against the legal framework for work-equipment use and recent literature on preventive maintenance, digital inspection and Maintenance 4.0. A retrospective analysis of 583 maintenance interventions recorded in 2025 found that most corrective failures (54.63%) were not anticipated by the current paper-based inspection, either missed by the operator or not covered by the instrument. The proposed model reorganizes the checklist by equipment systems and components, links each item to visual support, and applies an OK/NC/NA logic in which critical non-conformities force evidence capture, notification and equipment blocking. Configured as an interactive form on the SafetyCulture platform and applied in a preliminary test, the model confirmed that non-conformities trigger the intended actions and that inspection reports become immediately traceable. Although not yet subject to large-scale operational validation, the study demonstrates the limitations of paper-based inspection and the potential of a structured digital approach to strengthen pre-operational verification and risk control in demanding industrial environments.*

Keywords: *Digital checklist; Telescopic handler; Preventive maintenance; Occupational health and safety.*

1. INTRODUCTION

Telehandlers operate under demanding industrial conditions, being subject to mechanical stress, dust, temperature and humidity variations, and intensive duty cycles. These factors contribute to progressive degradation of mechanical components, increasing the probability of technical failure [1]. When used to lift personnel, telehandlers cease to represent a purely operational risk and become a direct threat to worker safety, with the potential to cause falls from height, crushing or other severe accidents. The use of load-handling equipment for lifting people is considered a conditioned use, subject to additional safety and verification requirements [2], and pre-operational inspection constitutes a key preventive measure prior to risk exposure [12].

Reliability-centred maintenance approaches are recognised as effective for increasing equipment availability and reducing unplanned downtime, since regular inspection prevents defects progressing into critical failure conditions [3]. Industry 4.0 approaches reinforce the importance of structured monitoring capable of anticipating failure throughout the equipment life cycle [4].

Among the instruments used to support these routines, the pre-operational paper checklist, typically completed by the operator at the start of each shift, should constitute a key tool for early anomaly detection. In practice, however, many checklists present important limitations, such as imprecise item descriptions, absence of visual guidance or excessive aggregation of verification points, which can lead operators to divergent interpretations, superficial checks or omission of critical verifications. Accident data reinforce the relevance of rigorous pre-operational verification: a Spanish study on accidents involving telehandlers and similar machinery identified thousands of work accidents associated with this type of equipment, including overturning, crushing, load falls, electrocution and falls during access [5], while the specialised literature identifies overturning, load instability and inappropriate platform use among the most frequent causal factors [6].

Paper checklists may also be incompletely filled, lost or damaged, and do not allow visual evidence to be attached, requiring additional transcription for supervisors or maintenance teams. Digital tools and mobile devices now allow these routines to become more structured and data-driven, enabling real-time information collection and faster communication [4].

Despite the growing interest in digitalising maintenance and inspection practice, the scientific literature still shows a scarcity of applied studies exploring the development of multimedia digital checklist models specifically adapted to telehandlers equipped with personnel-lifting platforms, particularly in industrial and mining contexts. This paper addresses this gap, taking as reference a Manitou MT 1335 telehandler used with a personnel-lifting platform, and proposes a structured, interactive digital instrument intended to improve early anomaly detection, support systematic verification and reinforce operational safety.

2. THEORETICAL BACKGROUND

The digitalisation of maintenance and safety management is closely associated with the development of Maintenance 4.0, which incorporates connectivity, structured data collection and real-time monitoring into inspection practice, supporting anomaly detection and asset-management decisions [4]. Checklists are, in general, understood not as a mere formulary but as a methodical tool that standardises what should be inspected, when and by whom, reducing the probability of omission or human error and increasing equipment reliability [3].

Well-designed preventive maintenance checklists have been shown to reduce unplanned downtime and equipment failure across industrial contexts, from off-road vehicle fleets [7] to semiconductor manufacturing [8], particularly when coordinated with maintenance scheduling and management oversight. At the same time, the literature on checklist use in other high-reliability settings, such as intensive care units, shows a more nuanced picture: checklists can improve adherence to best practice and reduce error rates when properly designed, but well-intentioned checklists may be ignored or answered superficially when they are too long, poorly worded or perceived as an administrative burden [9]. This is directly relevant to inspection tools for mobile lifting equipment, where item detail must be balanced against the time operators can realistically dedicate to pre-use verification.

Regarding the equipment itself, telehandlers present recurrent operational hazards associated with movement, manoeuvring and stability during lifting operations, with overturning recognised as a central mechanism in severe and fatal accidents [6]. When a personnel-lifting platform is added, these hazards are compounded by additional requirements at the interface between the equipment and the platform, reflected in specific technical standards for variable-reach trucks fitted with elevating work platforms for people [11]. European and national legislation establishes that employers must ensure work equipment is maintained in safe condition and verified before use [12],[13], with pre-use verification constituting the last confirmation of real operating conditions prior to worker exposure, and failures in these organisational control mechanisms are recognised as determinant factors in the genesis of occupational accidents [1].

Predictive and Industry 4.0 maintenance approaches further indicate that, once digitised, inspection data can be integrated with sensor measurements and failure history to support condition-based maintenance and more sophisticated planning models [4],[14]. This body of knowledge frames the central proposition of this paper: that a structured, digital, system-based checklist can act not merely as a documentation upgrade, but as an active organisational barrier against the progression of technical degradation into accidents.

3. METHODOLOGY

The study adopts a qualitative, document-based design, complemented by descriptive quantitative operational data, following a design-oriented research approach. In a first phase, the problem was identified through analysis of existing procedures and their weaknesses; in a second phase, technical analysis defined the structure and content of the digital checklist, which was then configured on a digital platform and applied in a test context to observe its functionality.

The empirical basis of the study relies on four documentary sources. The first is the operator's paper checklist currently in use, a one-page form organised into inspection phases (before starting the engine, after starting at idle, boom-movement tests from the cabin, end-of-operation checks, and compressor transport), with each item rated OK/Fault/N.A. and several items marked as critical points. The second source is the manufacturer's operator manual for the Manitou MT 835/1135/1335 family [15], detailing load capacities, lift heights and key safety systems. The third is an internal "Critical Points" brochure, labelling on annotated photographs the boom-lift cylinder pins and eyes, the platform tilt-cylinder pins, the boom extension-cylinder fixation points, boom welds, and the ANSUL fire-suppression actuators. The fourth source comprises the organisation's internal maintenance intervention records for 2025.

Documentary analysis followed a qualitative approach centred on systematically reading the four sources, identifying technical components and verification points, and comparing existing checklist items against manufacturer and regulatory recommendations. This process identified gaps, ambiguities and excessive aggregation — for instance, single lines combining distinct components under headings such as “condition of safety components (stops, bolts, pins, brakes, etc.) — critical point” — limiting an operator’s ability to report the specific failing component.

Checklist elaboration proceeded in three steps. First, every existing item was reviewed and coded by inspection phase and technical subsystem (general condition, access and fall protection, fire suppression, boom and platform structure, hydraulic system, tyres and wheels, transmission, controls and signalling), checking component scope, critical-point designation and clarity for non-native Portuguese speakers. Second, critical points already defined in the checklist were cross-referenced with the components visually identified in the Critical Points brochure, and aggregated items were split into individual, homogeneous sub-items, each attachable to a supporting photograph. Third, the refined item set was translated into a digital-platform specification, defining mandatory responses for critical points, forced attachment of a photograph, video or annotation whenever a non-conformity (NC) is recorded, and a blocking rule preventing the equipment from being declared operational while a critical NC remains open.

To reinforce the empirical grounding of the proposal, a retrospective, observational analysis was conducted on 583 maintenance interventions recorded in 2025 for a fleet of telehandlers operating in an underground mining context, covering equipment identification, intervention group (preventive/corrective), technical system, intervention time and, for corrective interventions, whether the underlying condition had previously been flagged on the pre-use paper checklist. This mixed-methods component followed maintenance-engineering practice that combines descriptive statistics with qualitative and normative analysis [1]. Each corrective intervention was cross-matched against the immediately preceding paper checklist to determine whether the failure had been previously signalled, missed, or concerned a component not covered by the existing instrument, without reinterpreting the technical cause of the fault. Data were anonymised at the organisation’s request and used exclusively for academic purposes.

The study is observational and retrospective, and does not support causal inference between prior signalling and subsequent maintenance decisions; the proposed model was not subject to large-scale experimental validation, but was applied in a preliminary test context. Validation of the proposed model therefore follows a strategy of conceptual triangulation across four dimensions: normative coherence (correspondence with Directive 2009/104/EC, Decree-Law No 50/2005 and applicable technical standards), technical coherence (correspondence with known failure modes of mechanical and hydraulic systems), operational coherence (elimination of interpretive ambiguity and introduction of explicit acceptance criteria) and preventive coherence (reinforcement of the pre-operational inspection as an organisational safety barrier).

4. RESULTS AND DISCUSSION

4.1. Proposed digital checklist structure

The resulting digital checklist preserves the inspection sequence already adopted by the organisation (before starting the engine, after starting at idle, boom-movement tests, end-of-operation, and compressor transport) while reorganising items into eight technical systems: general

condition, access and fall protection, boom and platform structure, hydraulic system, tyres and wheels, braking and steering, fire suppression, and controls and signalling. Within each system, items are broken down to a granular level, so that components previously aggregated under a single line — such as the boom's lower and upper lift-cylinder pins, the boom-extension fixation points and boom welds — are treated as distinct verification points, each linked to a specific image from the Critical Points brochure or the operator manual.

Acceptance criteria retain the three-level logic of the paper form but adopt safety-management terminology: OK (conforming), NC (non-conforming) and NA (not applicable). For non-critical items, an NC generates a traceable record for maintenance and safety review; for critical items, an NC automatically requires an annotation, a photograph or video, and a notification to maintenance and safety personnel, and prevents the equipment from being validated as operational until the anomaly is assessed and corrected by a competent person — a rule that was already implicit in the paper-based process but is now explicitly enforced. The digital record further structures metadata (date, time, location, equipment and operator identification, digital signatures of operator and supervisor) and item-level fields for observations and photographic evidence. The model was configured as an interactive form on the SafetyCulture platform and applied in a test context; the preliminary application confirmed that non-conformities trigger the intended actions (annotation, media attachment, deadline-bound corrective action and stakeholder notification) and that inspection reports become immediately available and traceable, indicating potential for future integration with maintenance dashboards.

4.2. Comparison between the existing and proposed checklist

Table 1 summarises the main structural differences between the paper checklist currently in use and the proposed digital checklist. The existing instrument frequently aggregates distinct components under a single critical-point heading; for example, one line inspecting the "condition of safety components (stops, bolts, pins, brakes, etc.) — critical point" covers components that, per the manufacturer's Critical Points brochure, correspond to ten physically distinct verification locations on the boom and platform structure. In the proposed checklist, this item is disaggregated into eleven individually numbered critical sub-items (11a-11k), each linked to a brochure image and requiring an independent OK/NC/NA response — raising dedicated critical-point verifications for this structure from one to eleven, while introducing control mechanisms absent from the paper-based process.

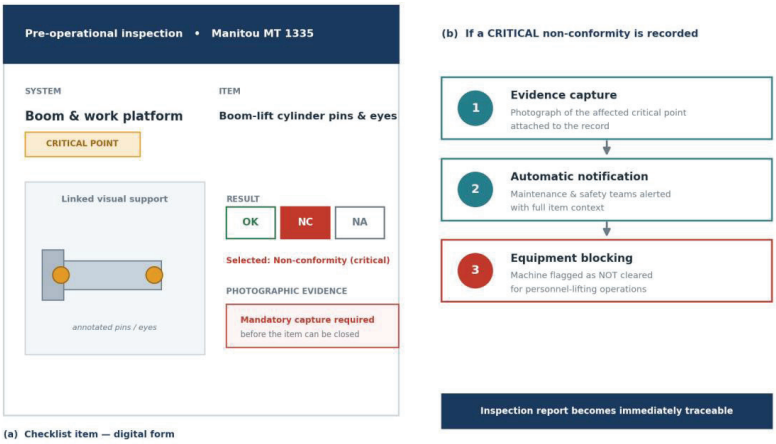


Figure 1. Illustrative example of a checklist item with linked visual support and the OK/NC/NA logic: a critical non-conformity triggers mandatory photographic evidence, automatic notification and equipment blocking. Schematic representation for illustration only; not an actual application screen or photograph.

Table 1: Comparison between the existing and the proposed checklist

Aspect	Existing paper checklist	Proposed digital checklist
Item structure	Aggregated items, covering several distinct components under one generic heading	Granular items; each isolated and linked to a specific component and supporting image
Boom/platform critical points (illustrative case)	1 aggregated critical item, covering 10 physical verification points	11 individually numbered critical sub-items (11a-11k)
Acceptance criteria	OK / Fault / N.A.	OK / NC / NA (same 3-level logic, safety terminology)
Evidence on non-conformity	Not required; declarative record only	Mandatory photograph or video for every critical NC
Escalation to maintenance	Manual, verbal or paper-based transmission	Automatic notification to maintenance/safety personnel
Equipment availability control	Not enforced by the instrument itself	Blocked as operational while a critical NC remains open
Traceability / metadata	Paper-based; no enforced structure	Structured digital record (timestamps, ID, signatures, photos)

4.3. Empirical assessment of the current inspection model

The retrospective analysis of 583 maintenance interventions recorded in 2025 shows that 70.33% were corrective and 29.67% preventive (Table 2), a distribution that, according to the maintenance-performance literature, is a typical indicator of reduced maturity in reliability-oriented maintenance systems [14].

Table 2: Distribution of interventions by group

Group	No. of interventions	Percentage (%)
Corrective	410	70.33
Preventive	173	29.67

Cross-matching the 410 corrective interventions against the pre-use paper checklists (Table 3) shows that only 45.37% of the underlying anomalies had been previously flagged by the operator, 34.39% had not been anticipated, and 20.24% concerned components not covered by the existing checklist at all — meaning that, overall, 54.63% of corrective failures were not anticipated by the current inspection model.

Table 3: Corrective interventions vs. prior checklist record

Checklist record	No.	%
Yes	186	45.37
No	141	34.39
Not existing (NE)	83	20.24

This pattern indicates that the paper checklist functions mainly as an observational record rather than an effective preventive decision mechanism: the absence of automatic escalation and of integration with the maintenance system prevents recorded information from being converted into timely technical action, a limitation consistent with the literature on non-integrated verification systems [16].

Analysing the 410 corrective interventions by technical system (Table 4) shows that electrical and electronic components — lighting, sensors, control circuits and wiring — account for the majority of corrective interventions (55.4%), followed by tyres (14.6%), the hydraulic circuit (9.5%), the engine

(7.1%) and general/structural items (4.1%); the remaining systems (cabin, chassis, lubrication, cooling, brakes, transmission) each contribute below 2%. The previous-flagging rate varies sharply by system: mechanically dominated systems such as the engine (79.3%), the hydraulic circuit (74.4%) and tyres (68.3%) are detected considerably more often before failure than electrical and electronic faults (31.7%), even though the latter are the single most frequent cause of corrective intervention. By type of action, most corrective interventions consisted of repairs (57.7%) or component replacement (21.0%), with a smaller share requiring reactive maintenance-type actions (12.8%) or simple verification (3.4%).

Table 4: Distribution of corrective interventions by technical system

System	No. (% of corrective total)	Previously flagged (%)
Electrical / electronic	227 (55.4%)	31.7
Tyres and wheels	60 (14.6%)	68.3
Hydraulic circuit	39 (9.5%)	74.4
Engine	29 (7.1%)	79.3
General / other	17 (4.1%)	29.4
Other systems (below 2% each)	38 (9.3%)	—

This asymmetry indicates that the preventive value of the existing checklist is concentrated on visually or manually verifiable mechanical components, while electrical and electronic faults — often linked to boom-movement control, lighting and sensor circuits — remain comparatively under-detected, reinforcing the case for a more granular, system-aware digital checklist. At item level, the four checklist items most frequently associated with previously flagged corrective interventions are tyre and wheel-bolt condition (41 interventions), driving/working lights, horn and beacon (32), boom-movement verification from the cabin (32), and hydraulic leaks and hose condition (26).

4.4. Discussion

The empirical results support the central argument of this paper: the limitations of the existing checklist are not solely a matter of operator diligence, but a structural feature of the instrument itself. A checklist that aggregates multiple components under generic headings, provides no automatic escalation and does not block operation in the presence of a critical non-conformity necessarily transfers detection to a later, more advanced stage of the failure process, consistent with maintenance-optimisation literature showing that functional failures are typically preceded by detectable degradation signals [1]. The digital checklist proposed in this study responds directly to this structural gap: granular, system-based items reduce the scope for aggregated, ambiguous ratings; mandatory photographic evidence for critical non-conformities reduces reliance on purely declarative judgement and supports remote severity assessment by maintenance personnel [16]; and the blocking rule for critical NCs converts pre-operational inspection from a documentation exercise into an active decision point that interrupts the causal chain between incipient defect and accident or major failure.

A further point concerns an apparent tension between the paper's strongest empirical finding and the focus of the redesign. Electrical and electronic faults are the largest source of corrective intervention and show one of the lowest prior-flagging rates, yet the granularity effort concentrates on the boom and platform structure, which represents a comparatively small share of interventions. This choice is deliberate and is justified on grounds of severity rather than frequency: unlike most electrical faults, a structural or hydraulic failure of the boom or platform during a personnel-lifting operation can be immediately catastrophic, so even low-frequency events warrant the most detailed,

image-linked verification. At the same time, it must be acknowledged that visual pre-use inspection has an inherently limited capacity to detect latent electrical and electronic faults — degraded insulation, intermittent sensor or wiring faults, incipient control-circuit failures — regardless of item granularity. For this class of failure, checklist granularity is complemented rather than replaced by condition monitoring and integration with maintenance telemetry; the checklist's contribution here is chiefly to capture and escalate externally observable symptoms, such as non-functioning lights, beacons or abnormal boom-movement responses, and to feed a data trail for later condition-based diagnosis.

These findings are consistent with similar applied studies. Rey et al. [16] found that structuring construction-site inspections as digital forms with mandatory field validation and photographic evidence substantially improved defect traceability over paper-based routines, mirroring the mechanism proposed here. The low preventive share found in this study (29.67%) matches the pattern Werbińska-Wojciechowska and Winiarska [14] identify as typical of organisations at an early stage of Maintenance

4.0 adoption. Case studies of preventive checklists in semiconductor manufacturing [8] likewise report that downtime reduction depends on coordination with maintenance scheduling, supporting the view that the detection gap found here (54.63%) reflects a structural, cross-sector limitation. Evidence from intensive care units [9] further cautions that structure alone does not guarantee compliance: checklists seen as an administrative burden risk superficial completion regardless of sector.

The preliminary nature of the test application means these are indications of functional viability rather than a statistically validated reduction in failures or downtime. Multilingual crews, noted in the studied context, add a further layer of interpretive risk that visual, image-based items can mitigate but not eliminate. Full validation will therefore require a structured pilot involving operators, maintenance technicians and safety professionals, together with systematic verification of every item against EN 1459-1, EN 1459-3, Directive 2009/104/EC, Decree-Law No 50/2005 and relevant good-practice guidance [10],[11],[12],[13]. It should be noted, however, that EN 1459-3:2015 addresses the truck–platform interface for lifting persons but explicitly excludes underground operation, so its requirements inform, but do not by themselves cover, the underground mining setting of this study, where site-specific rules must additionally apply.

5. CONCLUSION

This paper presented the technical design of an interactive digital checklist for the pre-operational inspection of a Manitou MT 1335 telehandler equipped with a personnel-lifting platform, developed through documentary analysis of the manufacturer's manual, the critical-points brochure and the current paper checklist, and applied in a test context on a digital platform. Analysis of the existing checklist revealed structural limitations — imprecise items, aggregation of distinct components, limited visual support and absence of non-conformity follow-up — and a retrospective analysis of 583 maintenance interventions confirmed that a majority of corrective failures (54.63%) were not anticipated by the current instrument, either missed by the operator or not covered by the checklist at all.

The proposed solution responds to these limitations by reorganising the checklist into granular, system-based items with explicit critical-point designation, maintaining the OK/NC/NA logic while requiring photographic evidence and blocking equipment validation in the presence of open

critical non-conformities. This transforms the pre-use inspection from a declarative record into an active barrier within the organisation's risk-control system, directly relevant given the elevated consequences associated with personnel-lifting operations.

Although the test application on the SafetyCulture platform provided preliminary, positive indications of functional viability, the study does not constitute an extensive experimental validation, nor does it quantify a resulting reduction in accidents or downtime. Future work should therefore prioritise a structured pilot with operators and maintenance technicians, systematic verification of all checklist items against EN 1459-1, EN 1459-3 and applicable legal requirements, user training centred on the safety rationale of critical items, and eventual integration of inspection data with maintenance history and telemetry to support condition-based and predictive maintenance. The contribution of this work lies in demonstrating that the preventive effectiveness of pre-operational inspection depends on its structure and its functional integration into maintenance and safety management processes, and in providing industry with a technically grounded and readily implementable model to that end.

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Original scientific paper

DEVELOPMENT OF SUSTAINABLE SYSTEMS FOR REDUCING THE FLAMMABILITY OF CELLULOSIC TEXTILES THROUGH THE APPLICATION OF ORGANOPHOSPHORUS COMPOUNDS AND ECO-FRIENDLY CROSSLINKING AGENTS

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Abstract: *Cellulosic textiles are widely used in protective equipment due to their physicochemical and mechanical properties, with functionalisation achieved through dry and wet finishing processes. Durable treatments for improving heat and flame resistance are commonly studied using organophosphorus compounds and crosslinkers for permanent bonding to cellulose, with emphasis on sustainable and cost-effective processes. This study investigates the replacement of a melamine crosslinker with citric acid in the presence of zeolite as a catalyst to develop a sustainable finishing process. The effectiveness of the treatments was evaluated by FTIR spectroscopy and mechanical testing. Flame resistance was assessed using the vertical flame test (ASTM D6413). Thermogravimetric analysis coupled with FTIR analysis (TG-IR) of evolved gases was performed before and after washing (HRN EN ISO 6330:2021). The results show that both treatments improve flame resistance compared to untreated fabric. The results show that both the conventional treatment based on an organophosphorus flame retardant and melamine crosslinker and the alternative treatment based on an organophosphorus flame retardant, citric acid, and zeolite improve flame resistance compared with untreated fabric The citric acid- and zeolite-based treatment exhibits a lower char length and better retention of mechanical properties, whereas the melamine-crosslinked treatment shows greater durability after washing.Based on the results of evolved gas analysis, together with the obtained high thermal stability and flame resistance values, it can be concluded that citric acid and zeolite represent a sustainable alternative for reducing the flammability of cellulosic textiles.*

Keywords: *cellulosic fabrics, flame retardants, citric acid, zeolite, TG-IR*

1. INTRODUCTION

Textile finishing comprises a wide range of processes aimed at improving the performance and functional properties of textile materials. Particular attention has been devoted to reducing the flammability of cellulosic materials, which, owing to their chemical structure and high cellulose content, exhibit high susceptibility to ignition and rapid flame propagation. The use of effective, environmentally friendly flame-retardant systems for the development of functional materials with reduced flammability enhances the safety of textile products while preserving their end-use properties [1,2]. Among the most effective flame-retardant systems for cellulosic materials are organophosphorus compounds. Upon heating, these compounds promote the formation of a protective char layer on the fibre surface instead of generating large amounts of flammable volatile degradation products. The resulting char barrier restricts heat and oxygen transfer to the material, thereby reducing the intensity of combustion. In combination with nitrogen-containing compounds, organophosphorus flame retardants exhibit a synergistic effect that further enhances flame-retardant performance [2,3]. Although organophosphorus systems have demonstrated high efficiency, certain halogen-containing flame retardants may generate toxic and hazardous combustion products, which has stimulated the development of halogen-free flame-retardant systems [3,4,5]. To achieve durable flame-retardant performance, organophosphorus flame retardants are commonly applied together with crosslinking agents. Most commercial systems are based on melamine–formaldehyde crosslinkers, which provide durable fixation of flame retardants to cellulose fibres and improve washing durability [5,6]. However, because of the presence of free formaldehyde, which poses risks to human health and the environment, increasing attention has been directed towards the development of formaldehyde-free alternatives [9]. Particular interest has been focused on polycarboxylic acids, especially citric acid, which forms ester bonds with the hydroxyl groups of cellulose, enabling more durable fixation of functional compounds to the textile substrate. Previous studies have shown that combinations of phosphorus-based flame retardants and citric acid provide effective flame retardancy while maintaining satisfactory mechanical properties of the treated material [6–9]. The effectiveness of phosphorus-based flame retardants for reducing the flammability of cotton fabrics has been confirmed in numerous studies, demonstrating significant improvements in flame resistance without substantial deterioration of mechanical properties [2–4,6–12]. Studies by Katović et al. [3,9] and Flinčec Grgac et al. [2,4,10,11] further demonstrated that citric acid can successfully replace conventional melamine–formaldehyde crosslinkers, providing satisfactory treatment durability and preservation of end-use properties while simultaneously reducing environmental impact. In addition, increasing attention has been devoted to the use of inorganic materials, particularly zeolites, owing to their high thermal stability, well-developed porous structure, and ability to function as environmentally benign heterogeneous catalysts. As such, zeolites represent a sustainable alternative to conventional acidic catalysts, which may have adverse environmental effects, while simultaneously contributing to the enhancement of the functional performance and flame-retardant properties of textile materials [12,13].

2. EXPERIMENTAL PART

2.1. Methodology

A 100% cotton fabric (N) with a warp density of 20 ends/cm, a weft density of 28 picks/cm, and a 4/1 satin weave was used in this study (fabric areal density not specified). The fabric was treated using two finishing formulations. The first formulation (ApI) contained 400 g/L of the organophosphorus flame retardant Apyrol CEP (CHT Group, Germany), 70 g/L of the low-formaldehyde KNITTEX 7636 melamine resin (Ciba, Switzerland), 30 g/L of H_3PO_4 catalyst (Kemika, Croatia), and 1 g/L of the wetting agent FELOSAN RG-N (CHT Group, Germany), with a pH of 3.74 at 22.4 °C. The second formulation (ApII) contained Apyrol CEP and FELOSAN RG-N at the same concentrations as ApI, together with 70 g/L citric acid (Sigma–Aldrich, Germany) as the crosslinking agent and 30 g/L zeolite A (Sigma–Aldrich, Germany), with a pH of 3.81 at 22.8 °C. The samples were impregnated using a laboratory padder (Benz, Switzerland) at a 100 % wet pick-up, dried at 110 °C for 2 min, and thermocondensed in a stenter (Benz, Switzerland) at 160 °C for 4 min. After treatment, part of the samples (ApI and ApII) was washed (ApI_W and ApII_W) in accordance with HRN EN ISO 6330:2021 [14] in a domestic washing machine (MIELE, Germany) at 40 °C for 30 min, using 5 g of phosphate-free and optical brightener-free detergent (WFK 88031).

2.2. Methods

The mechanical properties of the untreated and treated samples were evaluated by measuring the breaking force (Fp) and breaking elongation (εp) in both the warp and weft directions using a MesdanLab Strength Tester (Mesdan S.p.A., Italy), in accordance with HRN EN ISO 13934-1:1999 [15]. The physicochemical characterization of the samples was performed using Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) (PerkinElmer Spectrum 100, Shelton, USA). Four scans were recorded for each sample at a resolution of 4 cm^{-1} over the spectral range of 4000–380 cm^{-1}. Spectral processing and analysis were carried out using Spectrum 100 software (PerkinElmer). Thermogravimetric (TG) analysis was performed using a PerkinElmer TGA Pyris 1 (USA) with sample masses of 5–6 mg. The samples were heated from 50 to 850 °C at a heating rate of 30 °C min^{-1} under a continuous airflow. TG-FTIR analysis was carried out using a PerkinElmer Pyris TG analyzer, a PerkinElmer FT-IR spectrometer, and a TG-FTIR interface. A thermal analysis gas station (TAGS) equipped with an FTIR detector was used for evolved gas analysis. The transfer line, high-temperature gas cell, and TG interface were maintained at 280 °C throughout the measurements to prevent condensation. The evolved gases were transferred to the FTIR gas cell using a peristaltic pump at a flow rate of 60 mL min^{-1}. The flame resistance of the untreated and treated fabrics, before and after one washing cycle, was evaluated using the vertical flame test in accordance with ASTM D6413 [16].

3. RESULTS AND DISCUSSION

The results of the breaking force, breaking elongation, and time to break measurements for the untreated (N), treated, and washed samples are presented in Table 1. The ApI-treated samples exhibited a reduction in breaking force compared with the untreated fabric, with a more pronounced decrease in the weft direction (from 521 to 439 N) than in the warp direction (from 837 to 735 N). The ApI treatment had no significant effect on breaking elongation in the warp direction (from 7.56%

for the untreated fabric to 7.48% for ApI), whereas a decrease was observed in the weft direction (from 17.13% to 13.83%). In contrast, the ApII treatment increased the breaking force in the warp direction (from 837 to 929 N), while the value in the weft direction remained nearly unchanged (from 521 to 547 N). Breaking elongation increased in the warp direction (9.00%) and showed only a slight decrease in the weft direction (15.60%). Overall, both treatments caused only minor changes in breaking force and breaking elongation. However, the ApII-treated fabric exhibited slightly better mechanical performance, which may be attributed to the different pH of the treatment bath resulting from the use of zeolite as the catalyst.

Table 1. Mean breaking force and breaking elongation values of untreated and treated samples before and after washing.

Sample		Breaking force (N)	Breaking elongation (%)	Sample		Breaking elongation (N)	Breaking elongation (%)
N	warp	837	7.56	N_W	warp	668	14.41
	weft	521	17.13		weft	547	18.85
ApI	warp	735	7.48	ApI_W	warp	655	10.36
	weft	439	13.83		weft	434	15.49
ApII	warp	929	9.00	ApII_W	warp	716	12.61
	weft	547	15.60		weft	520	17.95

After one washing cycle, both treated fabrics show a decrease in breaking force and an increase in breaking elongation, which can be attributed to the partial removal of surface-unbound finishing components and relaxation of the material structure [3,7].

Physicochemical changes in the untreated and treated cotton fabrics before and after washing were investigated by FTIR-ATR analysis, and the obtained spectra are presented in Figures 1 and 2.

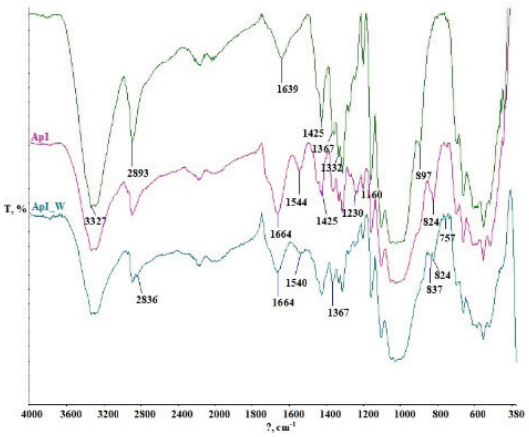


Figure 1. FTIR-ATR spectral curves of the untreated (N) and treated samples before (ApI) and after the washing cycle (ApI_W).

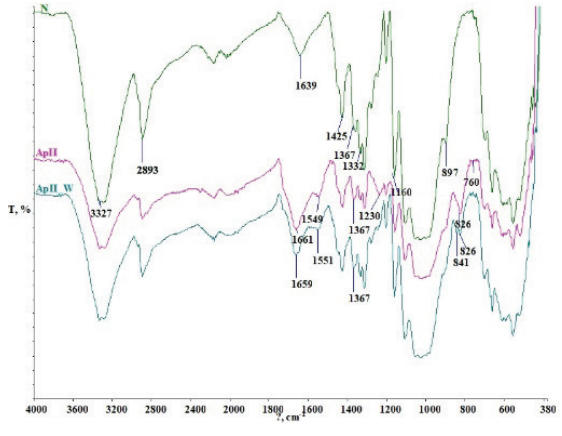
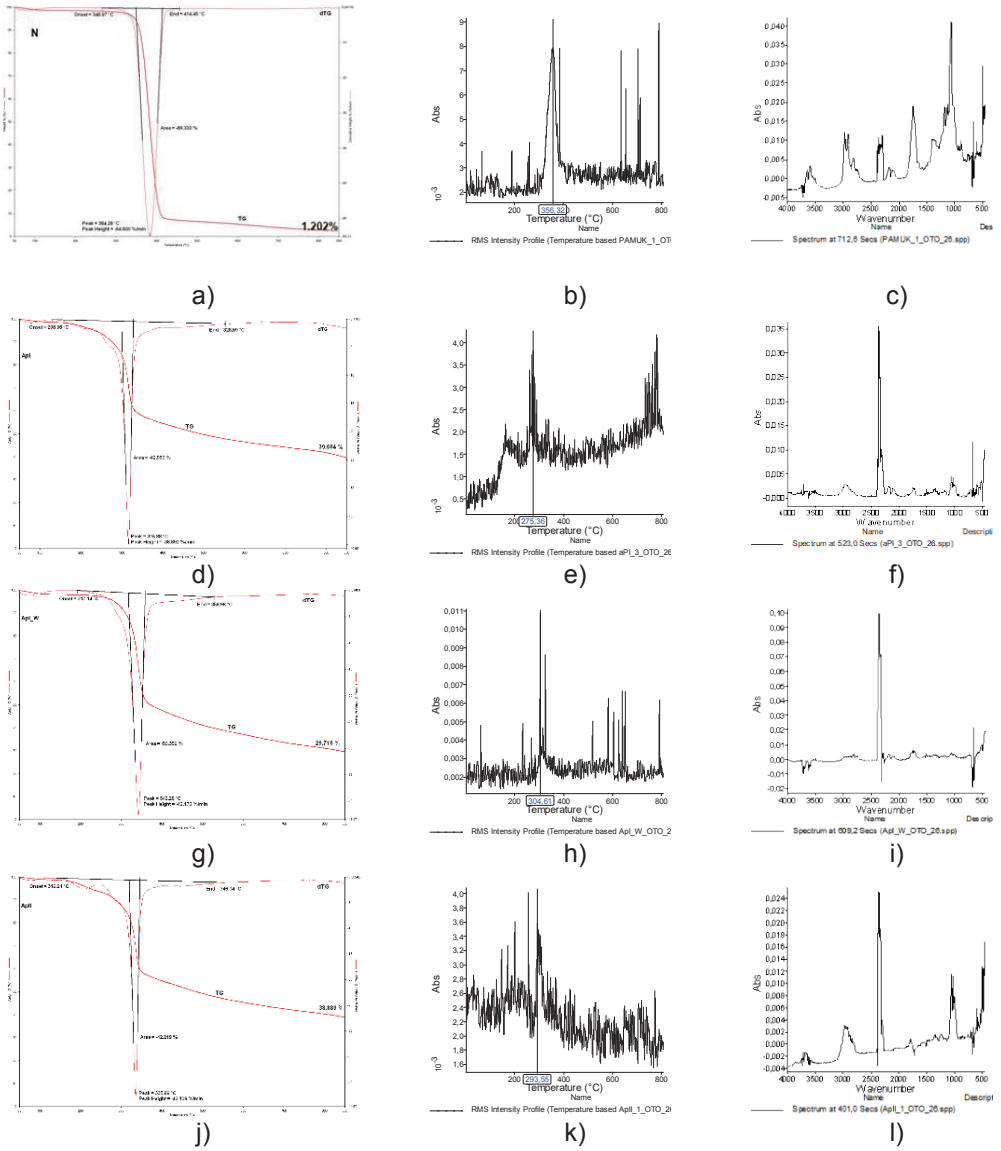
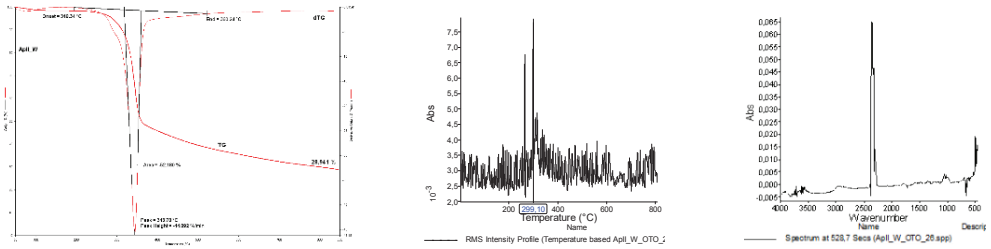


Figure 2. FTIR-ATR spectral curves of the untreated (N) and treated samples before (ApII) and after the washing cycle (ApII_W).

The FTIR spectrum of the sample treated with ApI shows clear changes compared to the untreated sample (N). The absorption band at 1639 cm^{-1}, originating from the bending vibration of adsorbed water in cellulose (δ(H–O–H)), shifts towards a higher wavenumber after treatment, with an increase in peak intensity. This shift can be attributed to changes in hydrogen bonding within the cellulose structure and partial overlap with vibrations of functional groups introduced by the treatment, indicating

successful chemical modification of the fibre surface. The appearance of new absorption bands at approximately 1230 and 826 cm^{-1} is associated with P=O and P–O–C vibrations formed due to the action of the organophosphorus flame retardant and the melamine crosslinking agent, confirming the bonding of phosphorus-containing groups to cellulose. The intense band at approximately 1542 cm^{-1}, observed both before and after washing in the ApI sample, can be attributed to N–H bending vibrations of the melamine-formaldehyde resin, confirming the presence of the crosslinker and the binding of the organophosphorus compound to the cellulose polymer [2,6–8]. The spectrum of the ApII-treated sample also shows a shift of the absorption maximum from 1639 to 1661 cm^{-1}, which remains stable after washing, confirming successful and durable chemical modification. The band around 1750 cm^{-1} is attributed to C=O stretching vibrations of ester groups formed by esterification of citric acid with hydroxyl groups of cellulose, confirming successful crosslinking [2,6]. The band in the region of 1520–1540 cm^{-1} can be assigned to asymmetric stretching vibrations of carboxylate ions (COO^-), indicating the presence of partially ionized carboxylic groups of citric acid or its ester derivatives bound to cellulose. The region between approximately 860 and 760 cm^{-1} can be associated with phosphorus-containing groups as well as Si–O–Si and Si–O–Al vibrations characteristic of zeolite [12]. The persistence of all these bands after washing confirms the durable fixation of the treatment on the surface of cotton fibres.





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Figure 3. TG-IR analysis of untreated and treated cotton fabrics before and after washing cycles: TG and dTG curves of N (a), absorption spectrum at the highest gas concentration at 464 °C (b), and IR-detected evolved gases at 464 °C; TG and dTG curves of ApI (d) and ApI_W (g), absorption spectra at the highest gas concentrations at 275 °C (e) and 304 °C (h), and IR-detected evolved gases at 275 °C (f) and 304 °C (i); TG and dTG curves of ApII (j) and ApII_W (m), absorption spectra at the highest gas concentrations at 293 °C (k) and 299 °C (l), and IR-detected evolved gases at 293 °C (n) and 299 °C (o).

The highest amount of gaseous decomposition products was recorded at 356.32 °C, corresponding to the region of maximum thermal degradation rate determined by dTG analysis. FTIR analysis identified characteristic absorption bands of carbon dioxide (2360–2345 cm^{-1}), carbon monoxide (around 2143 cm^{-1}), methane (3015 and 1306 cm^{-1}), aldehydes (1740–1720 cm^{-1}), and levoglucosan (1150–1000 cm^{-1}), which represent typical products of cellulose thermal degradation [18]. The obtained results confirm that the degradation of the untreated cotton fabric is associated with cellulose depolymerisation and the formation of flammable volatile products, accompanied by low thermal stability and almost complete degradation of the organic fraction. The treated samples show significantly higher thermal stability, as confirmed by the increased residue after thermogravimetric analysis: 39.664% for ApI (Figure 3d), 29.716% for ApI_W (Figure 3g), 38.889% for ApII (Figure 3j), and 28.881% for ApII_W (Figure 3m). TG-FTIR analysis of the treated samples revealed the presence of water, CO_2, and CO as the dominant gaseous decomposition products. At 293 °C, the ApII sample (Figure 3n) exhibits a lower CO_2 absorption intensity compared to ApI at 275 °C (Figure 3f), and the same trend is observed after washing, where ApII_W (299 °C; Figure 3o) shows lower CO_2 emissions than ApI_W (Figure 3i). These results confirm that the application of an organophosphorus flame retardant combined with citric acid as a crosslinking agent and zeolite as a catalyst represents an environmentally friendly and efficient system for improving thermal stability and reducing gaseous emissions during the thermal degradation of cellulosic materials.

The results of the mean values obtained from three specimens per sample during the evaluation of flame-retardant effects using the vertical flame test on untreated and treated samples before and after washing are presented in Table 2.

Table 2: Results of measurements of samples according to the standard test method for determining the flame resistance of textiles using the vertical flame test method.

Sample	Afterflame time (s)		Afterglow time (s)		Char length (mm)	
	Warp	weft	Warp	weft	Warp	weft
N	21	21	9	16	303	303
ApI	0	0	0	0	81	74
ApI_W	0	0.6	0	0	114	113
ApII	0	0	0	0	54	55
ApII_W	10	0	4	0	250	150

According to ASTM D6413, the flame resistance of fabrics was evaluated based on afterflame time, afterglow time, and char length, where lower values of these parameters indicate better resistance to flame exposure [18]. The untreated sample (N) showed behaviour typical of cotton materials, with a long afterflame time (21 s), afterglow time (9–16 s), and a maximum char length of 303 mm, confirming its low resistance to open flame. The ApI and ApII treatments significantly improved flame resistance, as evidenced by the absence of afterflame and afterglow and a markedly reduced char length. The ApI sample exhibited a char length of 81 mm in the warp direction and 74 mm in the weft direction, while the ApII sample showed substantially lower values (54 mm warp and 55 mm weft), indicating higher effectiveness of the treatment against open flame exposure. After washing, an increase in char length was observed for both ApI_W and ApII_W samples; however, the values remained significantly lower than those of the untreated fabric, confirming good durability of the treatment. These results indicate partial removal of the finishing agents during washing while maintaining a high level of flame protection. The results for ApI are consistent with literature reports on the synergistic effect of phosphorus and nitrogen in reducing the flammability of cellulosic materials [3], whereas ApII represents a significant advancement in terms of a more environmentally friendly flame-retardant system.

4. CONCLUSION

The results of this study demonstrate that environmentally friendly textile finishing methods can provide the desired functional properties, particularly improved resistance to heat and flame. FTIR analysis confirmed the presence of functional groups characteristic of the applied flame-retardant systems. The best flame resistance before washing was achieved by the ApII treatment, while the ApI treatment showed slightly better durability after washing; however, both treatments provided a high level of protection of the cellulosic material against heat and flame. Gas evolution analysis indicated that the ApII-treated sample, as a more environmentally favourable formulation, exhibited a significantly lower release of gaseous decomposition products before and after the washing cycle, particularly CO_2. Mechanical testing showed better preservation of breaking force and breaking elongation in samples treated with the ApII formulation. The obtained results indicate that citric acid and zeolite A can represent an effective and more environmentally friendly alternative to melamine-based crosslinkers in the flame-retardant finishing of cotton materials.

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Original scientific paper

IMPACT ANALYSIS OF THERMAL INSULATION DEGRADATION ON THE OPERATIONAL SAFETY OF EV HIGH-VOLTAGE SYSTEMS

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Abstract: *This study investigates the effect of elevated temperature exposure on the dielectric properties of high-voltage insulation materials used in electric vehicles (EVs). Experimental testing was conducted on Leoni Hivocar 150XE conductors at Rimac Technology facilities. Twenty-five samples were exposed to controlled thermal stress conditions at temperatures up to 220 °C in order to simulate extreme operating environments. Insulation resistance measurements were performed using a Kikusui TOS9303 analyzer. The results showed a 14.52% reduction in insulation resistance after thermal exposure, accompanied by visible material embrittlement. The findings indicate that thermal degradation significantly affects the dielectric stability of cross-linked polyolefin insulation materials and may reduce the operational safety margin of EV high-voltage systems. Results emphasize the importance of preventive diagnostics and thermal management in maintaining occupational safety during EV maintenance procedures.*

Keywords: *high-voltage systems, insulation, thermal degradation, Leoni Hivocar 150XE, occupational safety*

1. INTRODUCTION

Rapid growth in the use of electric vehicles (EVs) has increased the importance of high-voltage (HV) electrical safety during vehicle maintenance and servicing. Modern EV platforms commonly operate within Voltage Class B systems, typically between 350 V and 800 V. Such systems present additional occupational safety risks for service technicians and emergency personnel due to the possibility of electric shock caused by insulation failure or unintended contact with energized components. [1,2]

The primary objective of this research is to quantify the extent to which controlled thermal stress impairs the dielectric integrity of specialized EV conductors, specifically the Leoni Hivocar 150XE. [3] In the high-density packaging of modern battery packs and electric motor housings, insulation is frequently exposed to thermal peaks and mechanical vibrations. By measuring the degradation of these materials, this study establishes the actual safety margin remaining after extreme thermal exposure. These data points are essential for Occupational Safety and Health (OSH) frameworks, as measurable degradation directly correlates with a heightened risk of electric shock and the failure of vehicle safety systems designed to maintain the chassis at zero voltage.

2. EXPERIMENTAL PROCEDURE

The experimental methodology was designed to simulate the extreme thermal environments encountered in high-performance EV duty cycles and to measure the resulting impact on material stability.

2.1 Sample Preparation

Testing was conducted on a total of 25 samples of Leoni Hivocar 150XE conductors [3], evenly distributed into 5 experimental groups of 5 samples each (Figure 1). These groups included a control baseline at ambient temperature and four distinct thermal degradation groups exposed to 160 °C, 180 °C, 200 °C, and 220 °C, respectively. Samples were exposed to elevated temperature conditions for 120 minutes.

Each sample featured a 2.5 mm² cross-section and was cut to a uniform length of 300 mm. To eliminate the risk of conductor damage during preparation, a Schleuniger Multistrip 9480 (Figure 2) wire processing station was utilized for the automated cutting and removal of insulation from the cable ends, ensuring pristine electrical contact for subsequent diagnostic probing.

After thermal exposure, the samples were cooled to ambient temperature before electrical testing.



Figure 1: Wire test samples.

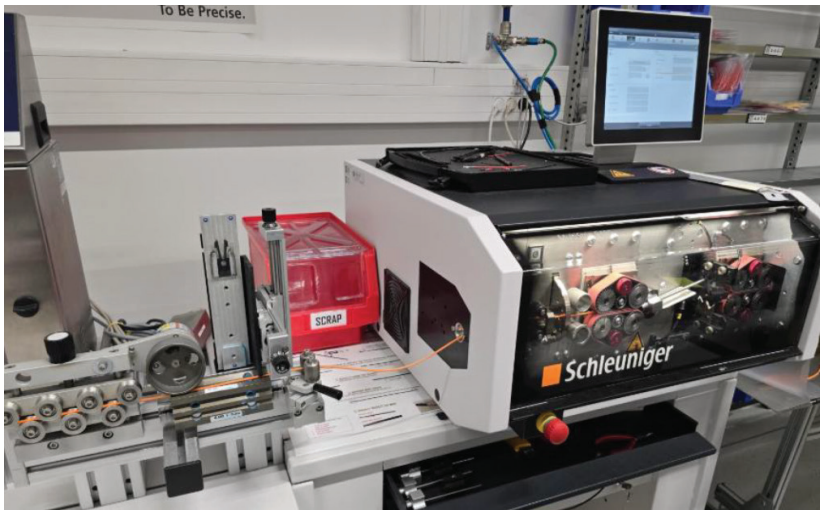


Figure 2: Schleuniger Multistrip 9480 wire processing station.

2.2 Testing Apparatus

The thermal stress and diagnostic and equipment utilized in this study are summarized in Table 1.

Table 1: Experimental Equipment Specifications.

Equipment Model	Purpose
Memmert UF260	Precision system for controlled thermal degradation and aging
Kikusui TOS9303	High-precision insulation and dielectric property analyzer

The high-precision analyzer Kikusui TOS9303, shown in Figure 3, was employed to perform both DC insulation resistance and AC leakage current evaluations.



Figure 3: Kikusui TOS9303.

2.3. Measurement Setup

A specialized 10kg weight jig (Figure 4) was integrated into the measurement setup. This apparatus was critical to standardize the mechanical load applied across the cross-linked polyolefin matrix during testing. By maintaining a constant 10kg load, the study effectively eliminated contact resistance variability and ensured that all measurements of insulation resistance and leakage current were repeatable and stable.

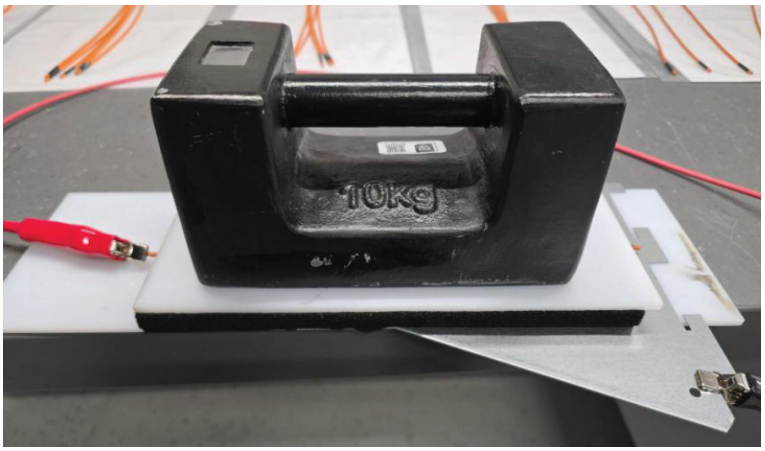


Figure 4: Sample clamping apparatus.

2.4 Environmental and Testing Conditions

All diagnostic measurements were conducted within a climate-controlled environment. Strict adherence to these ambient conditions was necessary to prevent humidity and temperature fluctuations from skewing the quantitative results of the dielectric analysis.

Measurements were performed at 22 ± 0.6 °C and relative humidity of 30 ± 2.8%.

Specifically, the DC insulation resistance evaluations were performed at a test voltage of 7200 V, while the AC leakage current measurements were conducted at 5000 V with a line frequency of 50 Hz.

3. RESULTS AND DISCUSSION

The results indicate a measurable decrease in dielectric performance following thermal exposure of radiation-crosslinked materials: while they exhibit superior melt resistance, they remain sensitive to dielectric and mechanical degradation under elevated thermal conditions.

Insulation Resistance (IR) Analysis identified a substantial drop in the dielectric performance of the insulation following exposure to temperatures of 220 °C. The comparative analysis against the initial baseline is presented in Table 2.

Table 2: Quantitative Analysis of Insulation Degradation

Sample group	Degradation temperature (°C)	Average resistance (GΩ)	Standard deviation
CONTROL	22	725.12	27.88
160	160	667.07	9.58
180	180	661.69	10.07
200	200	629.59	11.73
220	220	619.62	7.58

A corresponding increase in AC leakage current was observed, signifying a breakdown in the ability of the cross-linked polyolefin to contain the voltage. [4] To ensure the accuracy of AC measurements, a voltage ramp function (Figure 5) was utilized to eliminate the influence of initial capacitive currents. Although the Leoni Hivocar 150XE is rated as a Class D (150 °C) material, the 220 °C test environment pushed the polymer beyond its stabilized limits. The radiation-crosslinking process prevented the material from melting, but the thermal energy was sufficient to disrupt the polymer chain integrity, leading to the 14.52% IR drop (Figure 6). [5]

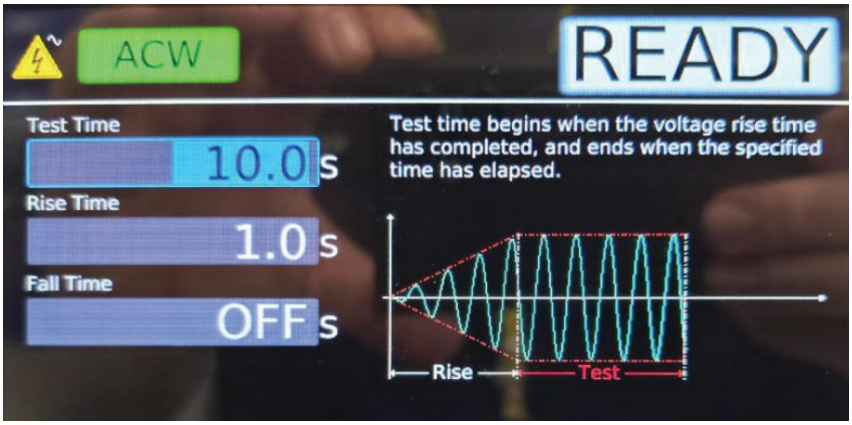


Figure 5: AC voltage ramp.

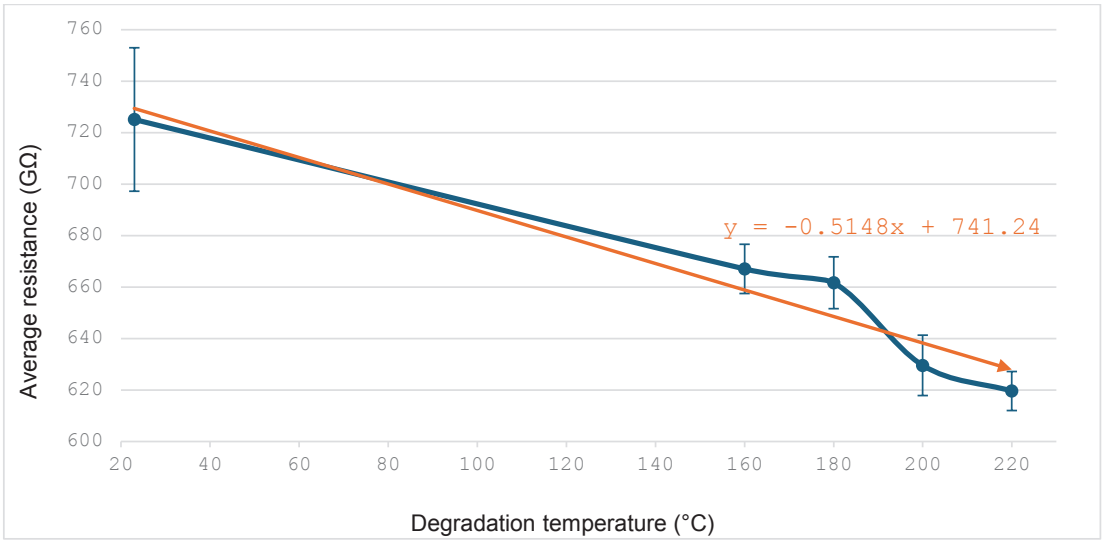


Figure 6: Decrease in insulation resistance.

Post-thermal inspection revealed severe polymer embrittlement. [6] The insulation, once flexible, showed reduced flexibility and susceptible to fracture under minor mechanical stress. In a vehicular application, such embrittlement represents a failure point; vibration-induced cracking could lead to exposed live conductors, facilitating short circuits or arc flash events.

While Leoni Hivocar 150XE cables are rated for Class D (150 °C) operation, this study confirms that excursions to 220 °C severely erode safety margins. The measured 14.52% decrease in insulation resistance, coupled with observed material brittleness, demonstrates that high-voltage integrity is highly sensitive to thermal history. [7, 8] To prevent electrical system failure, it is recommended

that EV maintenance protocols incorporate predictive diagnostics, specifically tracking insulation resistance trends to identify material fatigue before it reaches the threshold of a single-fault failure. [9, 10]

This study was limited to short-term thermal exposure of a single cable type. Long-term cyclic thermal loading, vibration effects, and combined electrothermal aging mechanisms were not investigated and should be considered in future research.

4. CONCLUSION

This study demonstrated that elevated thermal exposure negatively affects the dielectric properties of Leoni Hivocar 150XE high-voltage conductors. Experimental results showed a measurable reduction in insulation resistance together with visible material embrittlement after exposure to 220 °C. These findings indicate that thermal degradation may reduce the electrical safety margin of EV high-voltage systems during maintenance and operation. Continuous monitoring of insulation condition and adherence to thermal operating limits are therefore important for maintaining occupational safety and system reliability.

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Professional paper

IMPROVEMENT OF SAFETY AGAINST SPLITTING OF THE GARDEN TOOL WOODEN HANDLE WITH GLASS FIBRE-EPOXY REINFORCEMENT

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Abstract: *Garden tools were chosen for the test of increasement of strength by reinforcing the wooden handle by glass fiber-epoxy composite wrapped on the outer surface. Wood as a natural material, with CO2 capturing feature, has mostly favorable mechanical properties when used as a part of everyday tools. The significant specific shortcoming is the low strength perpendicular to its fibers, i.e., the splitting failure mode that arises from it. In this paper, a preliminary one test specimen measurement and calculation of the bending strength, is presented. As the first step, a measurement of the failure bending moment without the reinforcement was carried out. The failure mode was splitting in between the fibers, at an angle of approximately 7 degrees w.r.t. the longitudinal hoop axis (handle longitudinal centerline). In the second step, the failed handle was reinforced by the glass fiber - epoxy layers, with no post curing, and tested in the same manner. The results show that the two reinforcement layers of 160 g/m² of bidirectional glass fibre fabric, with NOVAPOXUV epoxy resin, 200 mm in length, increased the bending failure moment by 38.5%, relative to the original wood limit load.*

Keywords: *Wooden handle, Glass-fibre composite, Reinforced, Safety against splitting, Bending*

1. INTRODUCTION

Wood as the main CO2 capturing material is here chosen to show application of glass – fiber epoxy composite reinforcement. The garden tools have mainly a wooden handle. From the mechanical point of view, it possesses a favorable ratio of bending strength to density. The lighter the handle is, the less exertion the person using it over repeated actions feels. However, the wooden handles are mainly cut from a larger piece of timber, which quite often leads to severed fibers on the outer surface. This leads to significant lowering of the bending strength since the fibers tend to split (separate perpendicular to the fibers), rather than break in length. For this reason, many of the wooden handles have not been exploited to their possible maximum bending strength, when breaking strength of the fibers is fully utilized. This could be compensated, or improved, by adding some kind of reinforcement that would prevent the splitting failure mode from initiating, or better

to say, progressing. This is mainly achieved with some bandage – like reinforcement, either metal ring on several positions along the handle starting from the end of shovel metal sleeve – wood joint toward the end of the handle, or with a composite wrapping, or some other form of reinforcement. The aim of this research is to find how much, in terms of mass, of the glass fibers is needed to increase at least 25% of the handle bending strength. The length of the reinforcement and number of the layers are parameters which affect the reinforcement mostly. The length of the reinforcement was chosen to cover most of the splitted section of the handle.

2. METHODOLOGY, MATERIALS AND MEASUREMENTS

The garden tool chosen for this research is a shovel, shown in figure 1. In figure 1 a) the shown test shovel has a wooden handle with diameter at the joint with the metal part denoted as *d*, in amount of 39 mm. The wood type is beech, with a moisture content of around 12%.

a) b)

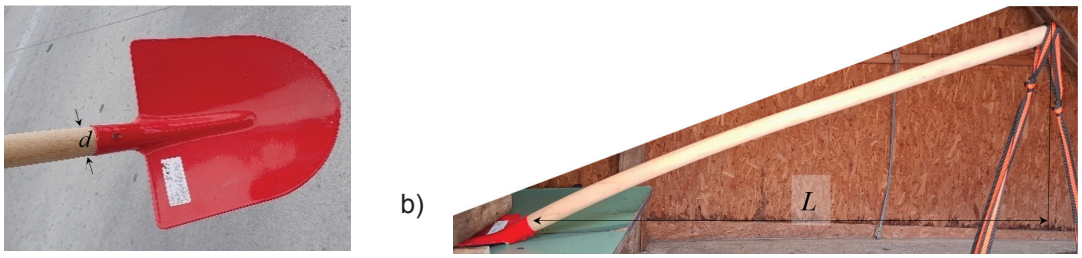


Figure 1: The test shovel: a) a top view, b) the test setup

The first step in the measurement was measuring the limit load of the handle “as is”, i.e., its bending load carrying capacity without strengthening. The test setup in shown in figure 1 b). The load was applied at the free end, through a couple of straps, as a free weight, measured on a digital scale with resolution of 5 g. The weight was created by adding smaller amounts of material measured with the said resolution. Deflection was measured in the vertical plane, by a measuring tape, with a resolution of 1 mm. A rigid rod was attached to the surrounding structure, and the deflection was measured as the distance from the horizontal rigid rod to the mark on the handle moving the vertical line of measurement as the handle tip traveled horizontally. Along with the vertical deflection of the handle tip, the horizontal distance from the fixed end of the metal sleeve (red circular part in the figure 1 b) to the vertical line of the weight center point, the *L* measure in the figure 1 b). Because of the inclination, in its nature, the handle deformation is nonlinear. The bending moment at each force value was calculated from the measures of the deformed shape, by the equation $M = FL$.

2.1. Natural load carrying capacity of the wooden handle

The wood used as cut from timber has an unknown fiber orientation, hence, an unknown angle of fibers, w.r.t. the longitudinal axis. If the fibers would have angle 0 deg to the longitudinal axis, then the problem of splitting would be significantly lower. The measurement of the bending strength is shown in diagram in figure 2. Splitting failure mode is shown in figure 3. The angle of the separated fibers to the longitudinal mid axis is around 7 degrees. The test sample withstood 328.5 Nm of static bending moment before failing by splitting.

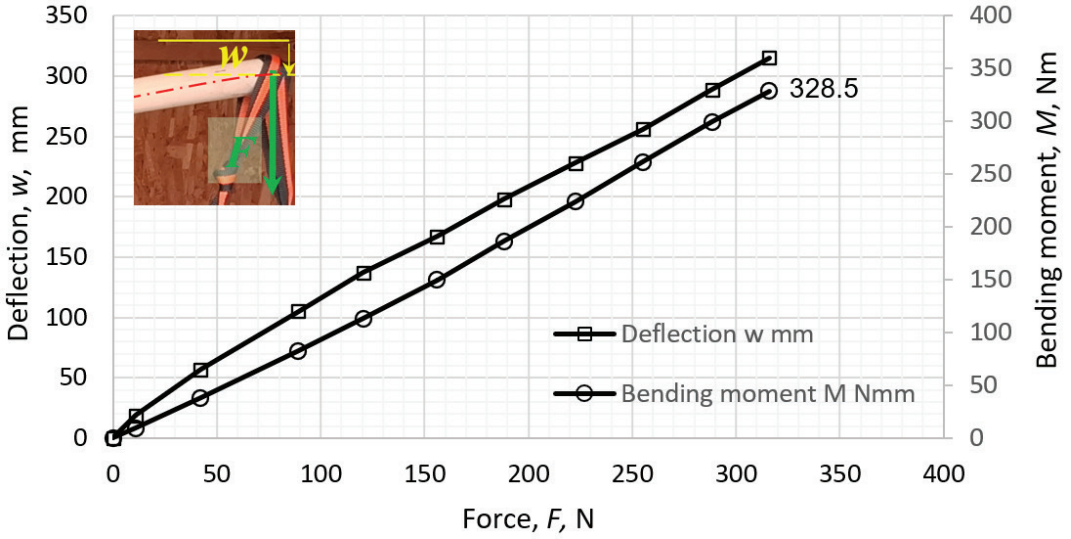


Figure 2: The force – deflection diagram for the original handle

a) b)

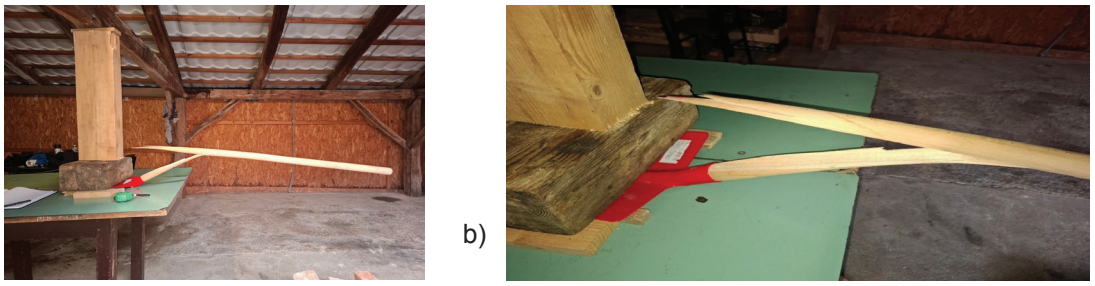


Figure 3: The damaged wooden handle: a) side view, b) enlarged view of the fibers

2.2. Load carrying capacity of the reinforced wooden handle

The glass fiber – epoxy reinforcement was applied in two layers, in length of around 200 mm. This is visible on the tested handle shown in figure 4. Chosen reinforcement length is 200 mm. This gives the mass of glass fibers of approximately 7.7 g. The epoxy resin used is NOVAPOXUV. The epoxy resin mixes in mass ratio A:B = 2:1. The amount of resin used was 15 g. The control of the resin before it began the reaction was achieved by wrapping the simple stretch foil around it. No post cure was conducted after the reaction. Measurement was conducted with the same methodology as the one for the original handle.

The reinforced handle withstood 455 Nm of static bending moment, shown in figure 5. At that point the longitudinally aligned glass fibers began cracking, while the wooden “core” remained functional. The increase in bending strength, relative to the original handle, is 38.5%. Since it is measured on one specimen, no statistical parameters can be shown. The orientation angle of glass fibers was chosen 0° w.r.t the handle longitudinal axis with the aim to utilize one half of the fibers for the increase of bending strength, and the other half for reinforcement of the radial load to the reinforcement due to splitting. Wider research in the effect of fibers angle is shown in [3]. Favorable effect of such external glass fiber – epoxy composite layers on beech wood specimens is shown in research paper [2], while for pine wood in [6].

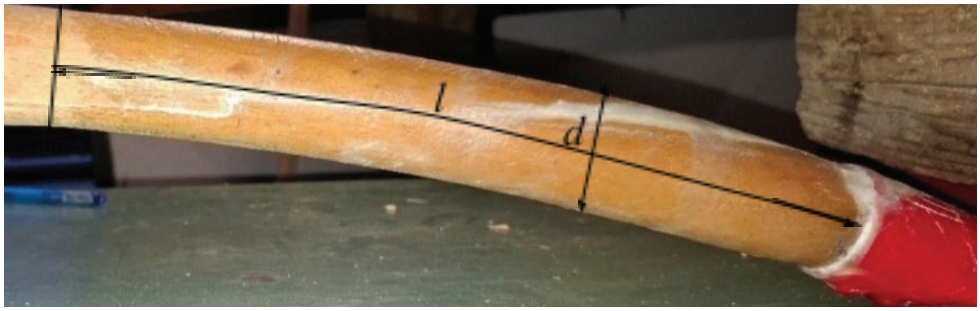


Figure 4: The test shovel handle with the reinforcement

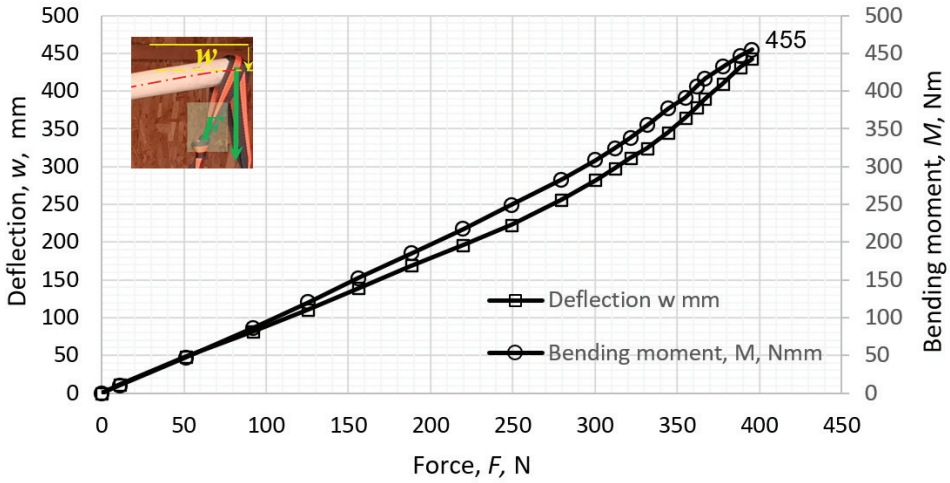


Figure 5: The force – deflection diagram for the reinforced handle

3. BENDING STRENGTH CALCULATION

Following the simplified bending behavior of Euler – Bernoulli beam, in this case, slightly curved (d/R < 0.05), [1 - 4], a stress distribution along -, and perpendicular to the wood fibers is adopted for the calculation of possible strength of a wooden handle of any given fiber orientation, shown in figure 6.

In figure 6, the black bold lines represent the wooden fibers. For the two failure modes, described by stress components in figure 6, the stress distribution is presumed linear over the section surface. This gives the bending strength, based on, the so far unknown limit stress, in breaking along the wood fibers, denoted in figure 6 a) as $\sigma_{||}$, and the strength perpendicular to the wood fibers, or strength against splitting, denoted in figure 6 b) as the $\sigma_{\perp}$.

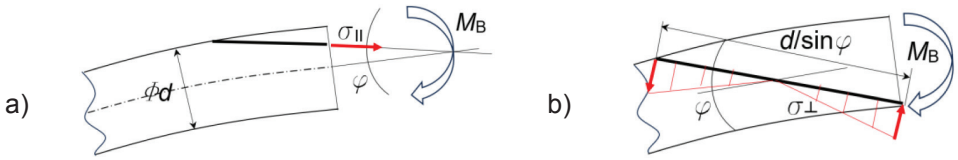


Figure 6: Stress distribution: a) breaking failure mode, b) splitting failure mode

Integrating the stress contribution for moment over the breaking surface, in figure 6 a) the cross – section, while in figure 6 b) an ellipsoidal surface, yields

$$M_B = 2\int_0^{d/2} \sigma_{II}^{lim} 2\cos(\varphi)\frac{z}{d} z\sqrt{0.25d^2 - z^2}\,dz \quad (a),$$
$$M_B = 2\int_0^{2d/\sin(\varphi)} \sigma_{\perp}^{lim} 2\sin(\varphi)\frac{s}{d} s\sqrt{\frac{0.25}{\sin^2(\varphi)}d^2 - s^2}\,ds \quad (b). \qquad (1)$$

Because of the complexity of the sub integral functions in , the Gaussian numerical integration scheme [2] was employed to solve the integrals. The parametric solution of the integrals in with the parameters σ_{II}^{lim}, $\sigma_{\perp}^{lim}$ as stress components at respectful failure modes, breaking and splitting, gives a lower limit for stress (strength) of the splitting mode, based on the measurement. The breaking stress limit is presumed higher for the same set of parameters, since that measurement could not be conducted, and did not occur. The bending strength, in the two modes based on the same fiber properties, as calculated for different fiber inclination angle, is shown in the diagram in figure 7.

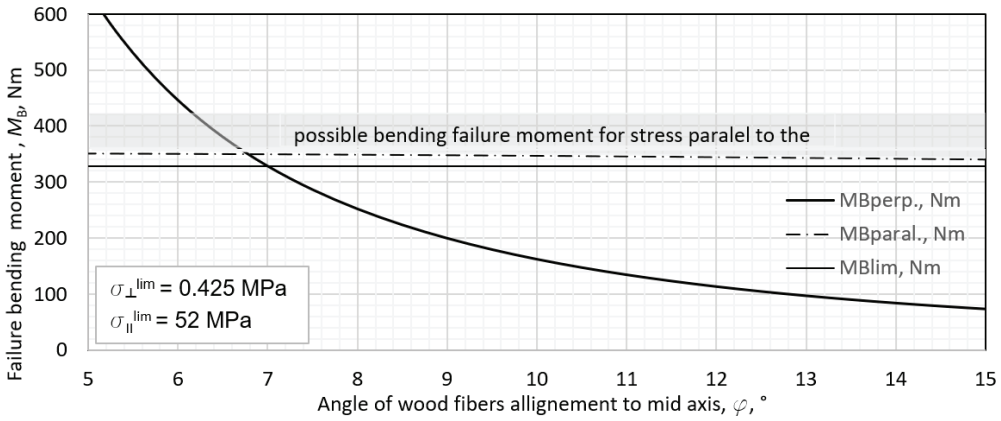
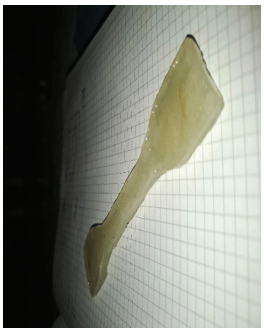


Figure 7: Two criteria failure bending moment

Another measurement conducted is the tensile properties of the glass fiber – epoxy composite, with its fibers aligned with the length of the specimen, shown in some detail in figure 8 a). Again, only one such sample was manufactured and measured. The glass fibers used in the bi-directional fabric have half of the total fibers positioned along the main load (stress) line, and the remaining half perpendicular to it. This was chosen for the reason of wrapping orientation of the composite reinforcement. The surface mass of the fabric is 160 g/m^2. The measurement data in quasi-static conditions is shown in figure 8 b),

The calculation gave the tensile strength of the fibers of approximately 1 045 MPa.

a) 

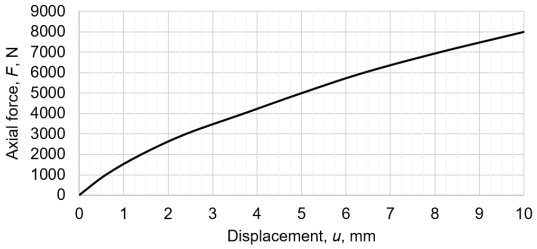
b) 

Figure 8: Testing of the glass fiber – epoxy tension properties: a) The specimen, b) The force – displacement diagram

4. CONCLUSION

This paper describes a reinforced wooden handle bending strength measurement. The first step was measurement of the wooden unreinforced handle bending strength. The force was applied at the handle tip as a free weight, not perpendicular to the handle's longitudinal axis of its starting shape, in steps. The handle's tip displacement was measured on the vertical line, so in its nature, this is a nonlinear deformation process. Deflections are large compared to the handle's cross section measure. The handle with no reinforcement failed at 328 Nm of bending moment, by splitting. The reinforcement consisted of two layers of BD (0/90°) glass fiber fabric, with surface density of 160 g/m^2, with NOVAPOXUV epoxy resin, in a foil type mold, with no post cure. Measured the same way, the reinforced handle failed at 455 Nm of bending moment, which is a yield of 38.5% relative to the wooden handle. The mass of the glass fibers applied is 7,7 g, and the mass of the epoxy resin 15 g.

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Professional paper

CONTRIBUTION TO THE OPTIMIZATION OF GEOMETRIC - DIMENSIONAL PARAMETERS OF TANKS AND EMERGENCY CONTAINERS IN OIL TERMINALS

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Abstract: *The preparation of the project task, the creation of the concept design, the creation of the main project with the construction of the tank and associated emergency containers, the revision of the main project, and the construction of oil terminals represent a very complex and interdisciplinary engineering task whose investments exceed tens of millions of euros. The above indicates the need to optimize the geometric-dimensional parameters of all associated terminal facilities. This paper focuses on optimization, primarily of vertical cylindrical tanks and associated emergency containers. This implies optimization of the costs of investing in the construction of terminal facilities with the aim of preserving the safety of tank structures and the ecological safety of people and the environment. Illustratively, a vertical cylindrical thin-walled tank with a 5.000 m³ volume with an associated emergency container at the oil terminal in Bihać will be used for the analysis of the structure and possible optimization.*

Keywords: *optimization, parameters, tank, emergency container, oil terminal.*

1. INTRODUCTION

The company "Operator - Terminali Federacije" d.o.o. Sarajevo has four oil storage terminals within the Federation of Bosnia and Herzegovina: Blažuj, Mostar, Živinice and Bihać, and an oil terminal in Port of Ploče in Republic of Croatia. Given that the construction, or complete reconstruction, of such terminal facilities today represents investments worth tens of millions of euros, the logical question of optimizing the costs of their construction arises. The paper focuses on optimization, primarily of vertical cylindrical tanks and associated emergency containers. This implies optimizing the costs of investing in the construction of terminal facilities with the aim of preserving the safety of tank structures, and the ecological safety of people and the environment.

Illustratively, the analysis of the structure and possible optimization will use a vertical cylindrical thin-walled tank with a fixed roof and a usable volume of 5.000 m³ with an associated emergency container at the Ribić oil terminal in Bihać. This terminal has a storage capacity of 18.100 m³, with two tanks of 5.000 m³ each and three tanks of 2.700 m³ each.

There are three conditions that are the prerequisite for the ecological safety of people and the environment [1]: a stable supporting structure of the impermeable shell and bottom of the tank; a geometrically and dimensionally capacitated and impermeable emergency container of the tank; and a technically correct terminal separator. Depending on the established optimization objective function, a possible contribution to geometric-dimensional optimization lies in defining the structure of the tank and the associated emergency container. The actual service life of the tank is longer than the recommended maintenance period of metal tanks (15-20 years), and therefore one of the most important issues is the remaining load-bearing capacity after the expiration of the maintenance period [1,7].

2. TECHNICAL SOLUTION OF TERMINAL FACILITIES

According to the available data, the value of the contract for the reconstruction of the S-105 Ribić terminal in Bihać is over 10 million euros and includes all five tanks with associated emergency containers and other terminal facilities (railway track, administration building, fuel transfer station, lubricant storage, fire protection system, cooling water supply system with the associated tank, roadways in the terminal facility, grease and oil separator, etc.). The reconstruction project works on the terminal are shown in Figure 1. The contracted works are expected to be completed by the end of the year.

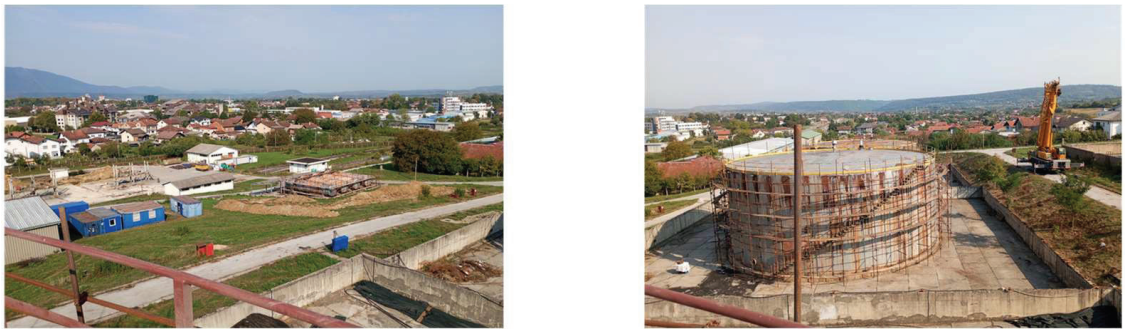


Figure 1: Terminal reconstruction works

Figure 1. on the right shows the selected geometric shape, namely a cylindrical vertical tank with a thin-walled shell, as the most optimal from the aspect of the value and distribution of stress in the shell [2-3]. It is also visible that the emergency container of rectangular geometric shape [1] is of appropriate dimensions and its volume is large enough to accommodate the entire amount of fuel in the event of a possible leak in the tank shell.

2.1. Optimization of the arrangement of the terminal's tanks and emergency containers

The usual arrangement of tanks and emergency containers is one tank and one emergency container, unless there is a lack of space on the land area where construction is planned.

In the case of lack of space for construction and in order to optimize the consumption of materials for the construction of the emergency container, it is possible to group two or three tanks into one common emergency container, which is capable of holding the entire amount of petroleum product in the event of failure of the shell of the largest tank in the group. Two or three tanks can be arranged in a line in a joint emergency container or three tanks can be arranged at the vertices of an imaginary equilateral triangle. [1]



Figure 2: Display of tanks in emergency containers

As shown in Figure 2, emergency containers can be square, rectangular or circular in shape, depending on the planned arrangement of tanks in the emergency container or whether the minimum material consumption for its construction will be set as a objective function [2,4]. It is important to note that the capacity of the emergency container must be 10% larger than the capacity of the associated tank and that the minimum distance between the tank shell and the emergency container wall is 3-5 meters to ensure working and handling space [1]. Emergency containers are constructed in such a way that they can accommodate the complete spillage of fuel from the tank and contain it until it is extracted [1].

2.2. Optimization of the dimensions of a vertical cylindrical tank

The basic dimensional parameters of a vertical cylindrical thin-walled tank are [1]: tank diameter, tank height, thickness of the steel sheet of the shell, roof and tank bottom. As an illustrative example, a cylindrical tank made of steel *S.0361*, intended for the storage of petroleum products with a specific gravity of up to *10 kN/m*^{3}, will be considered as a starting model [5,6]. The internal diameter of the tank is *Ø24.384 mm* [5]. The height, measured from the bottom of the tank to the internal surface of the protruding leg of the edge angle is *11.010 mm*. These dimensions allow the tank to have about *5.000 m*^{3} of usable volume [5].

The basic geometry and dimensions of the vertical thin-walled cylindrical tank with a flat roof and bottom are: diameter, *D = 24.384 m* and height *H = 11.010 m*.

The total surface *S* of a tank with a flat roof and bottom is calculated according to the formula:

$$S = S_{shell} + S_{roof} + S_{bottom} = \pi DH + 2 \cdot \frac{\pi D^2}{4} = \pi DH + \frac{\pi D^2}{2} \quad \textbf{(1)}$$

with:

$$S_{shell} = \pi DH \quad \textbf{(2)}$$

$$S_{\text{roof}} + S_{\text{bottom}} = 2 \cdot (\pi D^2/4) = \pi D^2/2 \quad \textbf{(3)}$$

The minimum total surface area of the tank shell, bottom and roof is set as the objective function, i.e. the minimum surface area of the sheet metal of assumed constant thickness, or the minimum amount of material used in the construction of a tank of known storage volume. [2,3,6]

$$f(D,H) = S(D,H) = \pi DH + \frac{\pi D^2}{2} \quad (4)$$

The volume of cylindrical tank is fixed and amounts to:

$$V_0 = \frac{\pi D^2}{4} H = \frac{\pi(24.384)^2}{4} \cdot 11.010 \quad (5)$$

That is $V_0 = 5.138{,}86\ m^3$.

The process of optimizing the total surface area of the tank *S* by limiting the storage volume of the tank $V=V_0$ will be presented using two methods: the method of derivation of the surface function and finding the minimum, and the method of Lagrange multipliers.

To prepare the derivative method, it is necessary to represent the surface area and volume functions of a cylindrical tank as follows:

$$S(D,H) = \pi DH + \frac{\pi D^2}{2} (shell + roof + bottom) \quad (6)$$

$$V_0 = \frac{\pi D^2}{4} H \qquad H = \frac{4V_0}{\pi D^2} \quad (7)$$

If H(D) is replaced in the equation for the surface S *(D, H)*, the following expression is obtained:

$$S(D) = \pi D \cdot H + \frac{\pi D^2}{2} = \pi D \cdot \frac{4V_0}{\pi D^2} + \frac{\pi D^2}{2} = \frac{4V_0}{D} + \frac{\pi D^2}{2} \quad (8)$$

By deriving the surface *S* by the parameter *D* and equating it to zero, we obtain:

$$\frac{dS}{dD} = -\frac{4V_0}{D^2} + \pi D \quad (9)$$

$$-\frac{4V_0}{D^2} + \pi D = 0 \quad \pi D = \frac{4V_0}{D^2} \longrightarrow \pi D^3 = 4\,V_0 \ \ldots\ldots D_{opt} = \sqrt[3]{\frac{4V_0}{\pi}} \quad (10)$$

Calculation of optimal height and surface of the tank is as follows:

$$H_{opt} = \frac{4V_0}{\pi D_{opt}^2} = D_{opt} \quad (since\ D^3 = 4\,V_0/\pi) \quad (11)$$

$$S_{opt} = \pi D_{opt} H_{opt} + \frac{\pi D_{opt}^2}{2} = \pi D_{opt}^2 + \frac{\pi D_{opt}^2}{2} = \frac{3}{2}\pi D_{opt}^2 \quad (12)$$

For V_0 *=5.138,86 m³*: D_{opt} *= 18,72 m*, S_{opt} *= 1.647 m²*.

Obtained result of the optimization will be the following:

$$D_{opt} = \sqrt[3]{4V_0/\pi} \quad (13)$$

To prepare for using the method of Lagrange multipliers, the objective function will be:

$$S(D,H) = \pi DH + \frac{\pi D^2}{2} \quad (14)$$

With defined limitation:

$$g(D,H) = \frac{\pi D^2}{4} H - V_0 = 0 \quad (15)$$

By forming Lagrange function, we obtain:

$$\mathcal{L}(D,H,\lambda) = \pi DH + \frac{\pi D^2}{2} - \lambda(\frac{\pi D^2}{4}H - V_0) \quad \textbf{(16)}$$

Differentiating with respect to *H* and *D,* and equating to zero gives:

$$\frac{\partial L}{\partial H} = 0: \qquad \pi D - \lambda \cdot \frac{\pi D^2}{4} = 0 \longrightarrow \pi D = \lambda \cdot \frac{\pi D^2}{4} \longrightarrow \lambda = \frac{4}{D} \quad \textbf{(17)}$$

$$\frac{\partial L}{\partial D} = 0: \qquad \pi H + \pi D - \lambda \cdot \frac{\pi}{2} DH = 0 \quad \textbf{(18)}$$

Entering $\lambda = 4/D$ in the previous equation gives:

$$\pi H + \pi D - \frac{4}{D} \cdot \frac{\pi}{2} DH = \pi H + \pi D - 2\pi H = \pi D - \pi H = 0 \quad \textbf{(19)}$$

That is, it finally follows that: $H = D$

The result of the optimization using the method of Lagrange multipliers shows that for the minimum tank surface, which is set as an objective function, the height of the tank should be equal to the diameter of the tank, i.e.: $H_{opt} = D_{opt}$ [3]

The volume of the illustrative tank example will be: $V_0 = 5.138{,}86\ m^3$ *and* $H = D$

$$V_0 = \frac{\pi D^2}{4} D = \frac{\pi D^3}{4} \longrightarrow D^3 = \frac{4V_0}{\pi} \quad \textbf{(20)}$$

$D = 18{,}72\ m = H$ (optimal tank dimensions)

The actual tank has a larger diameter $D=24.384\ m$ and height $H=11.010\ m$ for the same given tank volume of $V=5.000\ m^3$. The tank height-diameter ratio is $H/D=0.45$, which provides a lower center of mass and greater stability against overturning [4,5,6].

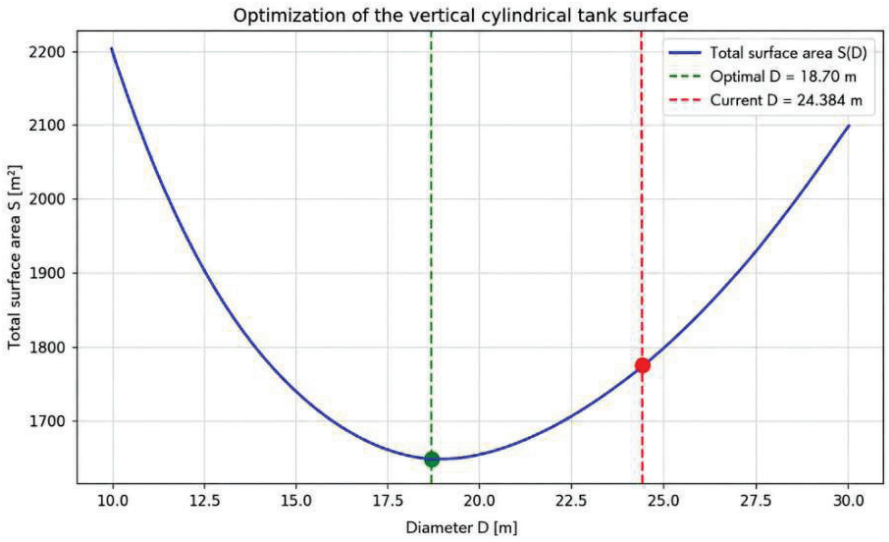


Figure 3: Graphic representation of the surface function *S(D)*

Figure 3 shows the diagram of the total surface area function *S(D)* where its minimum is visible, as well as the relation of current actual tank to the optimal one for the given objective function. The change in the dimensions of the actual tank resulting from the optimization reduces the

total surface area of the vessel (shell, roof, bottom) from 1.777 m^2 (existing tank) to 1.647 m^2 (optimized tank), i.e. by about 130 m^2, or *7.3%.*

According to research [5], the equivalent stress at the bottom of the existing tank with height (i.e. depth) *H=11.010 m*, diameter *D=24.384 m*, and sheet metal wall thickness *t=12 mm*, and filled with diesel fuel (ρ*=840 kg/m*^{3}) is approximately *92.3 MPa*. Compared to the allowable stress of *165 MPa* for *S.0361*, the stress amounts to about *56%*, and compared to the yield strength of *235 MPa*, it amounts to about *39%*.

For the tank with optimized dimensions $H_{opt}=D_{opt}$*=18.72 m* and sheet metal wall thickness *t=12 mm*, filled with the same diesel fuel, the equivalent stress at the bottom of the tank is approximately *120.3 MPa*. Compared to the allowable stress of *165 MPa* for *S.0361*, the stress amounts to about *73%*, and compared to the yield strength of *235 MPa*, it amounts to about *51%*.

3. CONCLUSION

From the limited and partially presented process of optimizing the arrangement of tanks and emergency containers, including the geometry and dimensions of the vertical tank, it is possible to conclude the following:

- optimization represents a serious tool for managing the costs of terminal construction;
- the next phase would be the optimization of the wall thickness by tank height levels;
- by optimizing the height-diameter *(H/D)* ratio of the tank, minimal steel consumption is achieved while meeting all safety criteria;
- reducing the total tank surface means reducing the required sheet metal surface, and thus reducing the total length of the weld, which contributes to the optimization of the construction of the tank;
- all stresses (circumferential, longitudinal and equivalent) are below the permissible stress and well below the tensile limit for both tanks.

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Review article

PHYSICAL PRINCIPLES AND SAFETY OF INDUCTION COOKTOPS

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Abstract: *Induction cooktops transfer electrical energy to compatible cookware by means of a time-varying magnetic field. This review paper presents the main physical principles of induction cooking, including electromagnetic induction, eddy currents, Joule heating, operating frequency and skin effect. It also examines thermal, electrical and electromagnetic safety, fire hazards, and possible interference with active medical implants. The main advantages are rapid heating, precise power control, high energy efficiency and the absence of an open flame. When correctly installed and used with suitable cookware, induction cooktops represent an efficient and generally safe cooking technology.*

Keywords: *induction cooktop, electromagnetic induction, Joule heating, electromagnetic fields, safety*

1. INTRODUCTION

Induction cooking is an application of electromagnetic induction in which electrical energy is transferred directly to suitable cookware and converted into heat. Unlike conventional electric cooktops, which use a resistive heating element, or gas cooktops, which rely on combustion, induction cooktops generate heat primarily within the base of the cookware. This method enables rapid heating, precise power control and lower heat losses to the surrounding environment [1], [2].

The increasing use of induction cooktops has also raised questions concerning their operating principles and safety. Although the absence of an open flame and a directly heated resistance element offer clear practical advantages, induction cooking is not free from potential hazards. The cookware and ceramic-glass surface can reach high temperatures, oil and food may overheat rapidly, and improper installation or damage to the appliance may create electrical risks. In addition, the time-varying magnetic field required for induction heating results in electromagnetic fields in the

immediate vicinity of the appliance. Their magnitude depends on factors such as the selected power level, cookware properties, positioning and distance from the cooking zone [3]–[5].

Particular attention is required for users of active electronic medical implants, as electromagnetic interference may occur under certain operating conditions. At the same time, current public-health assessments have not established convincing evidence of adverse health effects associated with the normal use of induction cooktops. Nevertheless, the limited number of studies addressing long-term exposure to medium-frequency magnetic fields supports the application of reasonable precautionary measures [5]–[7].

This review paper examines induction cooktops from both physical and safety perspectives. It first presents the principles of electromagnetic induction, including magnetic flux, Faraday's and Lenz's laws, the formation of eddy currents, Joule heating and the influence of operating frequency and skin effect. These principles are then related to the construction and operation of a domestic induction cooktop. The second part discusses thermal, fire, electrical and electromagnetic safety, as well as potential interference with active medical implants. Finally, the main advantages and limitations of induction cooking are considered, and practical recommendations for safe and efficient use are provided. By connecting the underlying physics with real operating conditions, the paper aims to provide a clear and balanced assessment of induction cooktop technology.

2. PHYSICAL PRINCIPLES OF ELECTROMAGNETIC INDUCTION

The operating principle of an induction cooktop is based on **electromagnetic induction**, a phenomenon first described by Michael Faraday in 1831. Electromagnetic induction refers to the generation of an electromotive force (EMF) in a conductor exposed to a time-varying magnetic field and represents one of the fundamental principles of classical electromagnetism [8], [9]. This principle forms the basis of numerous electrical devices, including transformers, electric generators, wireless charging systems, and induction heating equipment [9].

The fundamental quantity describing electromagnetic induction is the **magnetic flux**, defined as the amount of magnetic field passing through a given surface [8]. For a uniform magnetic field, the magnetic flux is expressed as

$$\Phi = B \cdot A \cos\theta \quad \textbf{(1)}$$

where B is the magnetic flux density, A is the surface area, and θis the angle between the magnetic field vector and the surface normal. More generally, magnetic flux is defined by the surface integral

$$\Phi = \int_S \boldsymbol{B} \cdot d\boldsymbol{A}. \quad \textbf{(2)}$$

Whenever the magnetic flux through a conducting loop changes with time, an electromotive force is induced. This relationship is described by **Faraday's law of electromagnetic induction**

$$\mathcal{E} = -N\frac{d\Phi}{dt} \quad \textbf{(3)}$$

where $\mathcal{E}$ is the induced electromotive force, N is the number of turns in the coil, and Φ is the magnetic flux [8], [9]. The negative sign represents **Lenz's law**, stating that the induced current always flows in a direction that opposes the change in magnetic flux responsible for its generation.

This behaviour is a direct consequence of the conservation of energy [8].

In an induction cooktop, an alternating electric current flows through a flat copper coil positioned beneath the ceramic-glass surface. The current creates a magnetic field whose magnitude and direction change continuously. When suitable cookware is placed above the coil, the changing magnetic field passes through its base and transfers electromagnetic energy to the conductive material [1].

Unlike a conventional electric cooktop, an induction cooktop does not primarily generate heat in a resistance element beneath the cooking surface. Instead, the electromagnetic field interacts directly with the cookware, causing the base of the pan or pot to become the main source of heat. This direct energy transfer allows rapid temperature changes and reduces unnecessary heating of the cooktop structure and the surrounding area [1].

2.1. Formation of Eddy Currents

As the magnetic field generated by the coil changes, the magnetic flux passing through the cookware also changes. According to Faraday's law, this changing flux induces an electromotive force along closed paths within the conductive base of the cookware. For one such path, the relationship can be written as

$$\mathcal{E} = -\frac{d\Phi}{dt} \tag{4}$$

where $\mathcal{E}$ is the electromotive force induced around a closed path, and Φ is the magnetic flux enclosed by that path [8], [10].

The base of the cookware does not contain a single predefined wire loop. Instead, it is a continuous metallic conductor containing mobile charge carriers. The induced electromotive force causes these charge carriers to move through the material along many closed paths. The resulting circulating currents are known as eddy currents [8], [11].

The current paths are commonly represented as circular or elliptical loops in diagrams of induction heating. In practice, their exact shape depends on the geometry of the induction coil, the dimensions of the cookware, and the spatial distribution of the magnetic field. The currents are therefore distributed throughout the region of the cookware that is exposed to the changing magnetic flux rather than being confined to a single line or circuit [1], [10].

The relationship between the induced electric field and the resulting current density can be expressed using the local form of Ohm's law:

$$\boldsymbol{J} = \sigma \boldsymbol{E} \tag{5}$$

where $\boldsymbol{J}$ is the electric current density, $\boldsymbol{E}$ is the induced electric field, and σ is the electrical conductivity of the cookware material. A stronger induced electric field generally produces a greater current density, provided that the material properties remain unchanged [9].

The magnitude of the induced electromotive force depends on how rapidly the magnetic flux changes. A faster variation of the magnetic field therefore produces a stronger induced electric field and can generate larger eddy currents. The strength and distribution of eddy currents depend on several other physical factors. These include the frequency and magnitude of the magnetic field, the electrical conductivity and magnetic permeability of the cookware, and the geometry and thickness

of its base [9], [1]. Ferromagnetic materials, such as cast iron and certain types of stainless steel, are particularly suitable for induction cooking because their magnetic properties improve the coupling between the coil and the cookware. Their high magnetic permeability helps concentrate the magnetic flux within the cookware base [1].

2.2. Joule Heating

As the eddy currents move through the metallic base of the cookware, charge carriers interact with the material structure. These interactions oppose the motion of the charges and result in the dissipation of electromagnetic energy as heat. For a simplified conductor represented by an equivalent electrical resistance, this energy-conversion process is described by Joule's law [9]:

$$P = I^2 R \tag{6}$$

where P is the thermal power, I is the induced current, and R is the electrical resistance. Equivalent forms of the same relationship are

$$P = UI \tag{7}$$

and

$$P = \frac{U^2}{R} \tag{8}$$

depending on the electrical quantities being considered. The total heat generated during a given period can be expressed as

$$Q = I^2 R t \tag{9}$$

where Q denotes the thermal energy produced and t is time.

In an induction cooktop, these equations describe the resistive losses associated with the eddy currents flowing through the base of the cookware. Because the currents are generated directly within the metal, heat is also produced directly within the cookware rather than first being generated in a separate heating element [9], [1].

The ceramic-glass surface is therefore not the primary heat source. It is heated mainly by thermal conduction from the hot cookware and only to a limited extent by its own absorption of energy. Areas outside the cooking zone generally remain cooler than those of conventional resistance cooktops, although the surface directly beneath a hot pan can still reach temperatures capable of causing burns [1].

The combination of electromagnetic induction, eddy-current formation, and Joule heating provides an elegant example of the direct conversion of electrical energy into thermal energy without intermediate heating elements. This physical principle explains why induction cooking achieves rapid heating, high energy efficiency, and improved operational safety compared with conventional electric resistance cooktops [1]. The working principle of an induction cooktop is schematically illustrated in Fig. 1.

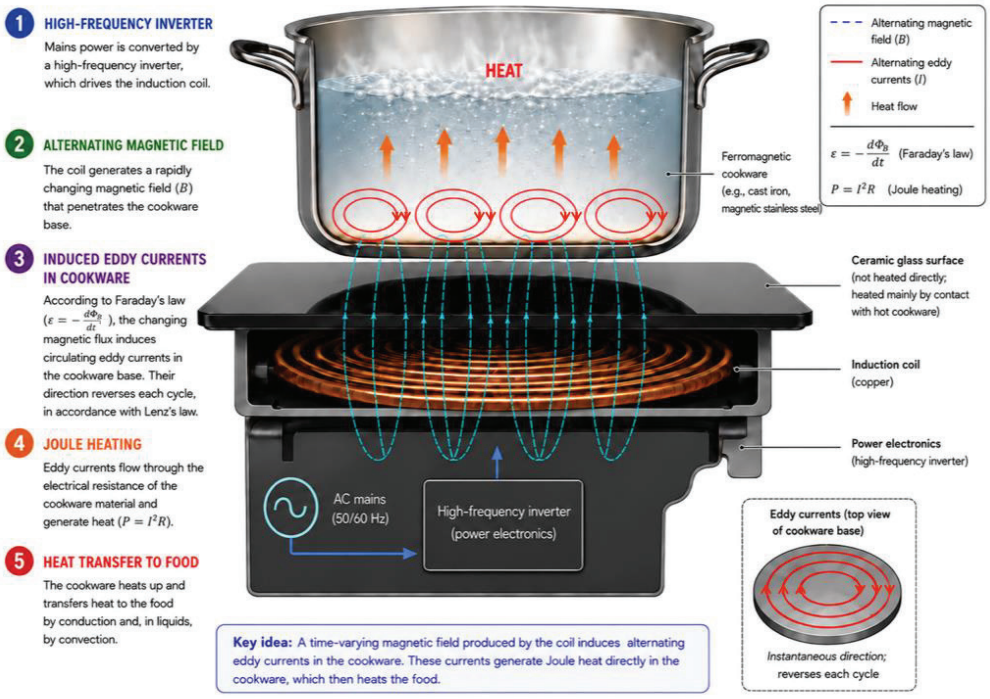


Figure 1: Working principle of an induction cooktop, Image generated by ChatGPT IMAGES, OpenAI, 30 June 2026, chatgpt.com.

2.3. Effect of Frequency and Skin Effect

The operating frequency also affects how deeply the alternating magnetic field penetrates the cookware and, consequently, how the eddy currents are distributed within its base. At relatively low frequencies, the induced current can be distributed through a larger part of the conductor. As the frequency increases, however, the current density becomes more concentrated near the surface exposed to the induction coil. This phenomenon is known as the skin effect [12].

The skin depth decreases as the frequency, magnetic permeability, or electrical conductivity increases. In ferromagnetic cookware operating at frequencies of several tens of kilohertz, the eddy currents are therefore concentrated mainly within a relatively shallow region of the cookware base. This reduces the effective cross-sectional area available for current flow and increases the effective electrical resistance encountered by the alternating currents. As a result, Joule heating is concentrated near the lower part of the cookware, where the electromagnetic coupling with the induction coil is strongest.

Frequency therefore has two related effects on induction heating. It influences the rate at which the magnetic flux changes and also determines how the resulting currents are distributed within the material. A higher frequency can strengthen the induced response and produce more localized heating, but increasing the frequency does not improve performance without limit. At very high frequencies, losses in the power-electronic converter and in the induction coil become more significant. The coil itself is also affected by skin and proximity effects, which increase its effective resistance. For this reason, induction coils are commonly constructed from Litz wire, consisting of many individually insulated strands designed to reduce high-frequency winding losses [13], [14].

The operating frequency of an induction cooktop is therefore selected as an engineering compromise. It must provide effective electromagnetic coupling and suitable heat generation in the cookware while limiting losses in the coil and power-electronic components.

3. SAFETY ASPECTS OF INDUCTION COOKTOP

The physical principles described in the previous section have direct implications for the safe use of induction cooktops. Since heat is generated mainly within the cookware, the surrounding cooking surface generally remains cooler than that of a conventional resistance cooktop. However, the ceramic-glass surface can still become hot through contact with the cookware and may remain at a temperature capable of causing burns after cooking has ended.

The safety of induction cooktops includes thermal and fire hazards, electrical safety, exposure to electromagnetic fields, and possible interference with active medical implants. General safety requirements for household cooking appliances are defined in IEC 60335-2-6, while IEC 62233 specifies methods for assessing electromagnetic fields produced by household appliances [3], [4].

3.1 Thermal, Fire and Electrical Safety

Modern induction cooktops typically include pan detection, residual-heat indicators, child locks, temperature monitoring and automatic switch-off functions. These features reduce the risk of unintended operation but do not replace normal cooking precautions [15].

The rapid heating response of induction technology requires particular attention when heating oil, fat, liquids or empty cookware. Such processes should not be left unattended, as overheating can occur within a short period. Fires involving hot oil or fat must not be extinguished with water; the appliance should be switched off and the flames covered with a suitable lid or fire blanket [16].

Metal objects such as knives, spoons or lids should not be left on an active cooking surface because they may become hot through electromagnetic interaction or contact with heated cookware. The cooktop should therefore not be used as a storage surface.

Electrical safety depends on correct installation, maintenance and ventilation. Built-in induction cooktops are high-power appliances and should be connected and repaired only by qualified personnel. If the ceramic-glass surface becomes cracked, the appliance should be disconnected from the power supply and should not be used until it has been inspected [16].

3.2 Exposure to Electromagnetic Fields

During operation, most of the magnetic field is coupled to the cookware. Nevertheless, a portion remains around the appliance as a stray electromagnetic field. Its magnitude depends on the cooktop design, selected power level, cookware material, dimensions and position. Correctly sized cookware placed centrally over the cooking zone improves electromagnetic coupling and reduces stray fields. Exposure increases when cookware is too small, off-centre or has a warped base. Magnetic-field strength also decreases rapidly with distance from the cooktop [5].

Current public-health reviews have not established convincing evidence of long-term adverse health effects caused by normal use of induction cooktops. However, the available research remains

limited, particularly for long-term exposure to medium-frequency magnetic fields. Precautionary measures such as using suitable cookware, centring it over the cooking zone and avoiding unnecessary close proximity are therefore reasonable [5], [6].

3.3 Active Medical Implants

People with cardiac pacemakers, implantable cardioverter-defibrillators or other active electronic implants require additional caution. Electromagnetic fields may interfere with certain devices, particularly when the user stands very close to the cooktop, the cookware is incorrectly positioned or the implant uses a more sensitive configuration [7].

Studies suggest that increasing the distance from the cooktop substantially reduces the possibility of interference. Users with active implants should follow the instructions of both the cooktop and implant manufacturers and consult their physician or implant clinic regarding appropriate separation distances [5], [7].

4. ADVANTAGES, LIMITATIONS AND RECOMMENDATIONS FOR SAFE USE

Induction cooktops offer several practical advantages. Heat is generated directly in the cookware, which enables rapid heating, accurate power control and reduced heat loss to the surrounding area. They are generally more energy-efficient than gas and conventional electric cooktops, although actual performance depends on the appliance, cookware and cooking method [2].

The absence of an open flame reduces combustion-related risks and avoids the production of combustion gases at the point of use. The smooth ceramic-glass surface is also relatively easy to clean, while functions such as pan detection, automatic switch-off and residual-heat indicators improve operational safety [15].

The main limitation is cookware compatibility. Suitable cookware must contain a ferromagnetic base, such as cast iron or magnetic stainless steel. Cookware should also be flat, undamaged and similar in size to the cooking zone. Incorrectly sized or warped cookware may reduce heating performance and increase stray electromagnetic fields [5].

The ceramic-glass surface can be scratched or damaged by rough cookware, heavy impacts or unsuitable cleaning methods. Cast-iron pans should therefore be placed carefully rather than dragged across the surface. Some users may also notice humming, clicking or fan noise during operation. These sounds are usually associated with the power electronics, cooling system or vibration of multilayer cookware and do not necessarily indicate a fault [17].

Safe use depends primarily on appropriate cookware and responsible user behaviour. Cookware should be centred on the selected zone, empty pans should not be heated, and high-power cooking should be supervised. Residual-heat indicators should be observed, and the appliance should be switched off manually after use rather than relying solely on automatic detection.

Where practical, users should avoid standing unnecessarily close to the front edge of the cooktop. The Swiss Federal Office of Public Health recommends maintaining a distance of approximately 15 cm and using rear cooking zones when prolonged close proximity cannot be avoided [5]. Users with active medical implants should follow device-specific medical guidance.

5. CONCLUSION

The complete physical process can be summarised as follows: an alternating current in the induction coil creates a time-varying magnetic field; the changing magnetic flux induces electromotive forces and circulating eddy currents in the cookware; and the electrical resistance of the cookware converts the energy of those currents into heat. The cookware then transfers the generated heat to the food, primarily by thermal conduction.

This direct conversion of electromagnetic energy into heat explains several important characteristics of induction cooking, including rapid heating, accurate power control, high energy efficiency, and reduced heating of surrounding components.

When correctly installed and used, induction cooktops combine rapid heating, precise control and high energy efficiency with a generally favourable safety profile. The remaining thermal, electrical and electromagnetic risks can be effectively reduced through correct cookware selection, proper positioning, regular supervision and adherence to manufacturer instructions.

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Professional paper

SAFETY ASSESSMENT OF INDUSTRIAL AND HOMEMADE WOOD SPLITTERS: A COMPARATIVE STUDY

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Abstract: *Wood splitters are commonly used in households, agriculture, and forestry for the preparation of firewood. Although they significantly improve work efficiency, they also represent a considerable source of occupational injuries, particularly injuries to the hands and fingers. The risk is often higher when using homemade wood splitters, which frequently lack appropriate safety features. The aim of this research is to analyze and compare the safety characteristics of industrially manufactured wood splitters and homemade wood splitters. The study focuses on the presence and condition of safety devices, machine construction characteristics, and the use of personal protective equipment during operation. Data are collected through machine inspections using safety checklists and surveys among users. The results are expected to identify common safety deficiencies and highlight differences in safety levels between the two types of machines*

Keywords: *wood splitter safety, occupational safety, homemade machinery, forestry equipment, machine safety devices*

1. INTRODUCTION

Vertical hydraulic log splitters represent an important segment of modern mechanization in firewood preparation, particularly in households, agricultural holdings, and small-scale production facilities. Their application enables efficient splitting of wood of various dimensions while significantly reducing the physical effort required from the operator, thereby increasing productivity and reducing the risk of injuries compared to traditional wood processing methods. [1]

Based on their design and safety characteristics, vertical hydraulic log splitters can be divided into professional (industrial) machines and homemade machines. Professional log splitters are designed in accordance with applicable technical standards and safety requirements, and they undergo testing and certification procedures before being placed on the market. Their construction includes standardized safety elements ensuring safe and reliable operation under demanding conditions. [2]

On the other hand, homemade log splitters are typically constructed using available components, without formal engineering design or standardized testing procedures. Although they may represent a cost-effective solution, their safety and reliability are not standardized and depend entirely on the knowledge and experience of the builder, which can significantly increase the risk of accidents and injuries during operation. Research in the field of machinery safety indicates that non-certified machines and deviations from prescribed safety requirements represent a significant risk factor in the wood processing sector. [3]

The aim of this paper is to compare the presence of key safety features between professional and homemade log splitters, in order to determine whether homemade log splitters are less safe to operate compared to professional ones.

2. MAIN SAFETY FEATURES OF LOG SPLITTERS

Safe operation of a firewood log splitter is extremely important due to the potential hazards that may arise during its use, such as crushing, cuts, and injuries caused by improper handling or technical malfunctions. Therefore, it is essential to be familiar with and apply the built-in safety features that reduce the risk of injury and ensure controlled and stable machine operation. [4]

The following are the main safety features:

A. PTO shaft guard on the pump

The PTO shaft guard on the log splitter pump primarily serves as a protection against injuries. The PTO shaft transmits mechanical energy from the tractor to the hydraulic system of the splitter. The guard prevents accidental contact between the operator and the rotating parts of the PTO shaft, thereby reducing the risk of serious injuries. Professional (industrial) log splitters are always equipped with a PTO shaft guard, which protects users from injuries. In practice, it has been observed that users often do not replace this component after it is damaged, but instead permanently remove it. Homemade log splitters rarely include this type of protection, which increases the risk of accidents. [5]

B. Two-hand operation system

This system requires the operator to simultaneously use both hands to activate the movement of the splitting wedge, meaning that the log splitter cannot be operated with one hand or by accidental contact. Professional (industrial) log splitters are equipped with a two-hand operation system as a key safety feature. However, in practice, it has been observed that many users remove or bypass this safety system in order to work faster. Homemade log splitters almost never include this safety feature, which significantly increases the risk of accidents. [4]

C. Hydraulic system safety valve

The safety valve in the hydraulic system of a log splitter serves as a key protective component that prevents system overload and thereby protects both the hydraulic assembly and the overall structure of the splitter from potential damage. In the event of pressure exceeding permissible limits, the valve is activated and relieves the system, ensuring safe and stable operation of the machine. In this way, the reliability of the machine is maintained and, most importantly, the safety of the operator is ensured. In both professional (industrial) and homemade log splitters, a safety valve is generally installed in the hydraulic system as a basic protection element against overload. The difference lies in the fact that, in professional splitters, these valves are properly installed and correctly adjusted by experts, whereas in homemade splitters, the quality of installation and adjustment is uncertain, which may affect operational safety. [6]

D. Anti-slip working surface

The anti-slip working surface on a log splitter is designed to prevent the wood from slipping during positioning and splitting, thereby increasing stability and overall operator safety. In professional (industrial) log splitters, this feature is always present as a standard safety component, while in homemade log splitters it is often completely absent, which increases the risk of unsafe operation. [2]

E. Stable and robust construction

A stable and robust construction of a log splitter is essential for operator safety, as it ensures reliable and safe machine operation without unwanted movement, vibrations, or structural deformation during use. Such a design enables the splitter to withstand high loads generated during operation while maintaining a stable position and control, thereby reducing the risk of injuries. In professional (industrial) log splitters, the construction is always designed to be stable, strong, and safe for operation. In contrast, in homemade log splitters, the stability and structural strength are sometimes not adequately addressed, which can increase the risk of unsafe operation. [2, 7]

F. Side support for holding unsplit pieces of wood

The side support for holding unsplit pieces of wood on a log splitter is important because it provides the operator with a designated place to rest unsplit pieces of wood. This reduces the need for constant manual handling of unsplit pieces of wood within the working area of the splitter, thereby improving visibility and overall safety, as well as reducing the risk of accidents during operation. In professional (industrial) log splitters, this feature is almost always included as standard equipment, whereas homemade log splitters may not always have it, although it is quite often present. [7]

G. Side lifting attachment for positioning wood into the working position

The side lifting attachment for positioning wood into the working position is designed to facilitate safer and easier lifting and placement of heavy pieces of wood onto the splitting working area. This reduces physical strain on the operator and lowers the risk of injuries. In professional (industrial) log splitters, such an attachment is often included as standard equipment, whereas homemade log splitters rarely have this feature. [7]

H. Clearly defined instructions for use, maintenance, and machine markings

Clearly defined instructions for use and maintenance, as well as markings on the log splitter, including the CE marking, are important because they provide the user with clear information about safe operation, proper maintenance, and the limitations of the machine. This helps reduce the risk of misuse and injuries. In professional (industrial) log splitters, such instructions and markings are always present in accordance with EU requirements, whereas in homemade log splitters they are most often absent. [7, 8]

3. RESEARCH METHODOLOGY AND RESULTS

Market analysis was conducted on vertical hydraulic log splitters powered via a power take-off (PTO) shaft. The analysis included a total of 15 samples, of which 5 were professional (industrial) log splitters (Table 1) and 10 were homemade units. The purpose of the analysis was to compare the presence of key safety features between professional and homemade log splitters, in order to determine whether homemade splitters are less safe to operate compared to professional ones.

Additionally, a short survey was conducted among users working with log splitters (both professional and hobby users) to determine whether they use personal protective equipment (PPE).

Table 1. Professional (industrial) log splitters – sample overview.

Sample	Model	Drive type	Declared splitting force (tons)
1	KRPAN CV 22 K PRO	PTO	21
2	UNIFOREST TITANIUM 23	PTO	21
3	LANCMAN STX 21 MULTISPEED	PTO	21
4	BALFOR PRO 22 BIG	PTO	22
5	AMR VPF 22	PTO	22

An overview of 10 homemade log splitter samples shows that all units are powered via a PTO (power take-off) drive system. For all observed machines, the declared splitting force is unknown, indicating a lack of technical documentation or standardization. This highlights a common limitation of homemade equipment, particularly in terms of specification transparency and safety assessment.

3.1. Results - Analysis of vertical hydraulic log splitters

Professional (industrial) log splitters (Figure 1) are equipped with all essential safety features prescribed by relevant standards and regulations. These features are mandatory to ensure safe operation of the machine and adequate protection of the operator. [2, 7, 8]

The analysis shows that all observed professional log splitters fully meet (100%) these safety requirements, with all key safety features consistently implemented. This indicates a high level of standardization, reliability, and compliance with safety regulations.



Figure 1. Professional industrial log splitter – KRPAN CV 22 K PRO.

The analysis of safety features in homemade log splitters (Figure 2) showed that such machines very often lack certain safety elements that are essential for safe and reliable operation. In addition, even those safety features that are implemented are often executed in a technically questionable manner. Based on the analysis (Table 2 and Figure 3), homemade log splitters generally allow faster operation compared to professional (industrial) machines, primarily due to the reduced number of safety features that may slow down the working process. However, this simplified design results in a significantly lower level of operational safety compared to professionally manufactured log splitters.

Table 2. Safety features analysis of homemade log splitters.

	A	B	C	D	E	F	G	H
Sample 1	NO	NO	YES*	NO	N/A	NO	NO	NO
Sample 2	NO	NO	YES*	YES	N/A	YES	YES	NO
Sample 3	NO	NO	YES*	NO	N/A	YES	YES	NO
Sample 4	NO	NO	YES*	NO	N/A	NO	NO	NO
Sample 5	YES	NO	YES*	NO	N/A	YES	NO	NO
Sample 6	NO	NO	YES*	YES	N/A	YES	NO	NO
Sample 7	NO	NO	YES*	NO	N/A	NO	NO	NO
Sample 8	NO	NO	YES*	YES	N/A	YES	NO	NO
Sample 9	YES	NO	YES*	NO	N/A	YES	NO	NO
Sample 10	NO	NO	YES*	NO	N/A	NO	NO	NO

Description of symbols:

A -> PTO shaft guard on the pump

B -> Two-hand operation system

C -> Hydraulic system safety valve

D -> Anti-slip working surface

E -> Stable and robust construction

F -> Side support for holding unsplit pieces of wood

G	->	Side lifting attachment for positioning wood into the working position
H	->	Clearly defined instructions for use, maintenance, and machine markings
YES	->	Safety feature present
NO	->	Safety feature absent
*	->	Implemented in a technically questionable manner
N/A	->	Unknown



Figure 2. Homemade log splitter.

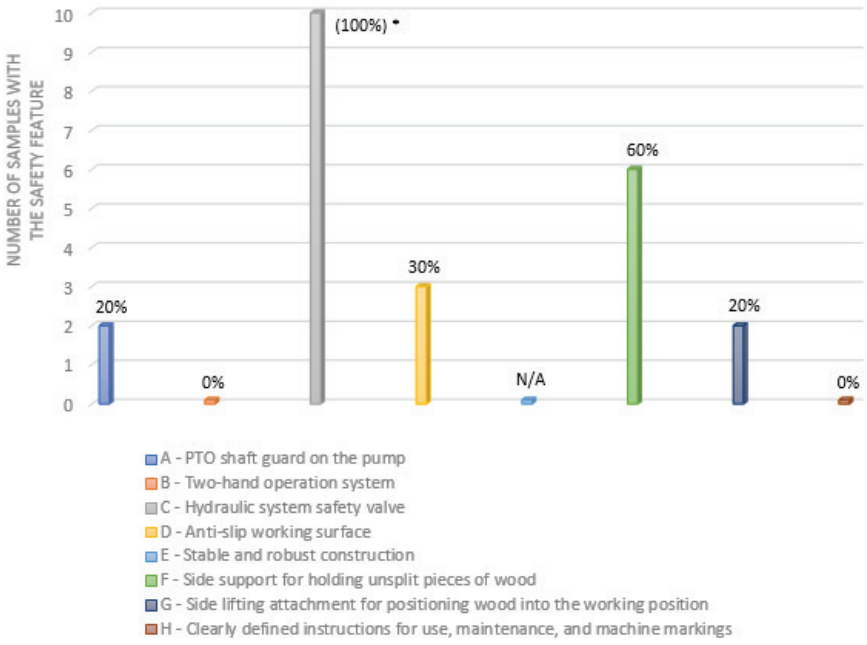


Figure 3. Presence of safety features in homemade log splitters.

3.2. Results - Personal protective equipment when operating a log splitter

Personal protective equipment (PPE) includes protective gear used by the operator to reduce the risk of injury during log splitter operation and to ensure an additional level of safety. The proper and consistent use of this equipment is essential for safe and responsible work. [9, 10]

Personal protective equipment when operating a log splitter typically includes:

- protective clothing,
- protective gloves,
- safety footwear with reinforced toe caps,
- safety glasses or a face shield,
- a safety helmet,
- hearing protection (earmuffs or earplugs), if necessary.

Among professional users, this equipment is generally used regularly and consistently in accordance with safety regulations. In contrast, among hobby users, the practice is significantly weaker, and most often only protective gloves are used, while other equipment is frequently omitted, which increases the risk of injuries.

4. CONCLUSION

Based on the conducted research, it can be concluded that there are significant differences in safety levels between professional (industrial) and homemade log splitters. Professional log splitters fully comply with prescribed safety requirements and are equipped with all key safety features, ensuring a high level of operator protection and reliable machine operation. In contrast, homemade log splitters often lack essential safety components or have them implemented in a technically questionable manner, which significantly increases the risk of accidents and injuries during operation.

Although homemade log splitters may enable faster operation due to the absence of some safety systems, this advantage comes at the cost of reduced safety. Furthermore, the lack of technical documentation, standardization, and clear operating instructions further complicates their safe use.

The study also found that the use of personal protective equipment is more consistent among professional users, while hobby users tend to apply it less frequently, which additionally increases the risk of injuries.

In conclusion, the results highlight the need for improved user education regarding homemade machinery, as well as the importance of implementing safety features and adhering to proper safety practices in order to reduce occupational risks.

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Professional paper

DEVELOPMENT AND EXPERIMENTAL VALIDATION OF A MECHATRONIC SYSTEM FOR AUTOMATIC INDOOR LIGHT CONTROL IN WORK ENVIRONMENTS

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Abstract: *This paper presents the design and experimental validation of a mechatronic system for automatic control of indoor light levels aimed at improving workplace conditions. The system integrates a microcontroller-based control unit, a digital light sensor, and a stepper-motor-driven mechanism to maintain a target illumination level in real time. The proposed solution contributes to technical-technological protection factors by improving visibility and supporting safer working conditions. The control algorithm continuously monitors ambient light and adjusts the mechanism position according to predefined parameters, ensuring stable and energy-efficient operation. Experimental results confirm reliable performance, high sensitivity to illumination changes, and safe operation. The solution also reflects multidisciplinary aspects by integrating mechatronics, ergonomics, and energy efficiency, making it suitable for application in modern work environments.*

Keywords: *microcontroller-based systems, stepper motor control, light sensors, workplace safety*

1. INTRODUCTION

Adequate lighting conditions are an important factor in creating safe, comfortable, and energy-efficient indoor work environments. Insufficient illumination may reduce visibility and negatively affect user comfort, while excessive reliance on artificial lighting increases energy consumption and operating costs. Modern building standards increasingly emphasize sustainable design principles and efficient utilization of natural resources, including daylight as a primary source of indoor illumination. Natural lighting conditions continuously vary due to weather conditions, time of day, and seasonal changes. Maintaining a constant illumination level therefore requires dynamic adjustment of shading elements or artificial lighting systems. Automated solutions capable of adapting to changing environmental conditions are becoming an important component of modern smart building technologies [1].

This paper presents the development and experimental validation of a mechatronic system for automatic indoor light control. The proposed solution uses a digital light sensor, a microcontroller-based control unit, and a stepper-motor-driven mechanism to automatically adjust window blinds according to ambient illumination levels. The objective of the system is to maintain a predefined illumination level while minimizing user intervention and improving indoor environmental conditions. The developed prototype combines sensing technologies, embedded programming, automatic control, mechanical design, engineering calculations, and additive manufacturing into a single functional system.

The proposed solution was developed using readily available and cost-effective components, demonstrating that functional automation systems can be implemented without significant financial investment. In addition to its practical application, the developed prototype has educational value, as it integrates several engineering disciplines, including electronics, embedded systems, mechanical design, automatic control, and additive manufacturing [2]. The resulting system demonstrates the feasibility of a low-cost mechatronic solution for automatic illumination control that can contribute to improved workplace conditions, increased utilization of natural daylight, and enhanced energy efficiency in modern indoor environments.

2. SYSTEM ARCHITECTURE

The developed system combines electronic and mechanical subsystems into a unified mechatronic solution for automatic indoor light regulation. The operating principle is based on continuous measurement of ambient illumination, processing of sensor data, and conversion of electrical energy into mechanical motion used for blind positioning. To achieve a low-cost and easily reproducible implementation, the system was developed using components from the widely adopted Arduino ecosystem, which provides an open-source hardware and software platform suitable for rapid prototyping and educational applications. The availability of compatible sensors, motor drivers, and software libraries enables efficient integration of individual subsystems into a functional automation solution.

The electronic subsystem consists of a BH1750 digital light sensor, an Arduino Uno microcontroller, an A4988 motor driver, a user interface module, and supporting electronic components. Ambient illumination is measured using the BH1750 sensor, whose operation is based on a silicon photodiode that converts light into a photocurrent proportional to light intensity. The measured signal is internally amplified and converted into a digital value expressed in lux, allowing direct processing without additional calibration. The sensor module and an enlarged view of the photodiode are shown in Figure 1. Communication between the BH1750 sensor, the microcontroller, and the display module is established through the I2C communication bus, which enables bidirectional data exchange using only two signal lines.

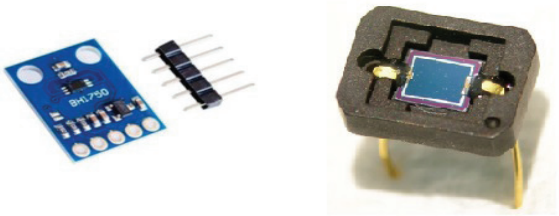


Figure 1: BH1750 digital light sensor and enlarged view of the photodiode [3,4]

Motor control is performed using an A4988 stepper motor driver, which acts as an interface between the microcontroller and the NEMA 17 stepper motor. The driver receives STEP and DIR signals generated by the microcontroller and converts them into controlled current sequences supplied to the motor windings. The STEP signal determines the number of motor steps, while the DIR signal defines the direction of rotation. To ensure reliable operation under load, the driver was configured for a maximum motor current of 1.4 A, corresponding to the operating requirements of the selected stepper motor. Since the driver dissipates heat during operation, an aluminium heatsink was installed to improve thermal management and prevent overheating. Proper current adjustment and thermal protection are particularly important for maintaining stable motor performance and ensuring long-term system reliability. The electrical connections of the A4988 driver are shown in Figure 2.

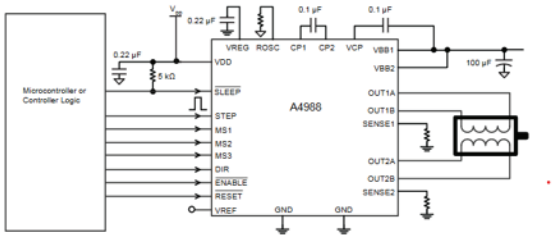


Figure 2: Electrical connections of the A4988 stepper motor driver [5]

The interface between the electronic and mechanical subsystems is realized through a NEMA 17 (42HS40) bipolar stepper motor. The motor converts electrical energy into controlled rotational motion, enabling precise positioning of the blind mechanism. With a step angle of 1.8°, the motor requires 200 steps for a full revolution, providing sufficient positioning accuracy for automatic illumination control applications. Owing to its positioning precision, repeatability, and compatibility with microcontroller-based control systems, the selected motor represents an effective solution for low-cost mechatronic automation applications. The generated rotational motion is transmitted to the blinds through a custom-designed mechanical transmission system described in the following section. Figure 3 illustrates the electronic control system and its interface to the stepper motor.

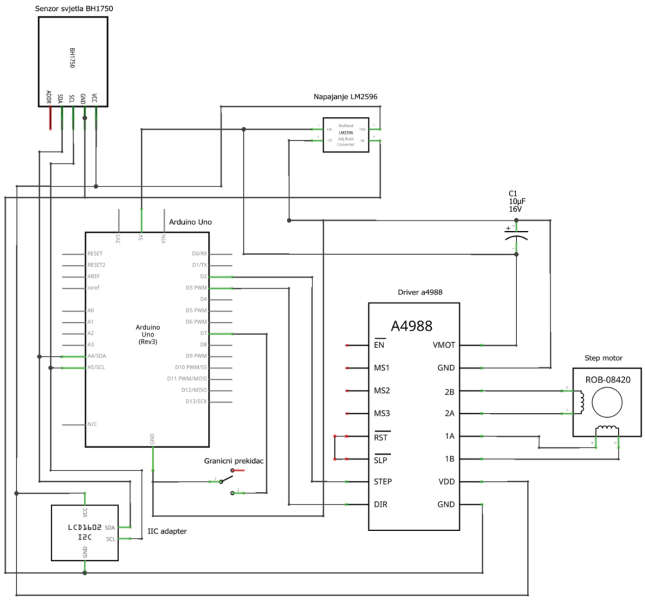


Figure 3: Wiring diagram of the developed electronic control system [6]

3. MECHANICAL DESIGN AND PROTOTYPE DEVELOPMENT

The mechanical subsystem was developed to transfer the rotational motion generated by the stepper motor to the blind mechanism while providing sufficient torque and positioning accuracy. Since the blinds represent the primary mechanical load of the system, particular attention was devoted to the design of the transmission mechanism and supporting structural components. During the design process, the expected load conditions and required driving torque were analysed to ensure reliable operation of the system. Based on these considerations, a reduction gearbox was incorporated between the motor and the output shaft. The selected transmission ratio increases the available output torque while reducing the influence of load variations and improving the smoothness of blind movement. This approach enables stable operation without placing excessive demands on the motor and driver.

The mechanical design was developed using CATIA CAD software, allowing detailed modelling of all structural and transmission elements before manufacturing. The assembly consists of a motor mount, gearbox housing, transmission gears, shaft supports, and an output shaft connected to the blind mechanism. Since the majority of components were intended for production using fused deposition modelling (FDM) 3D printing technology, the design was optimized for additive manufacturing while ensuring adequate rigidity, simple assembly, and reliable operation during repeated actuation cycles. This approach enabled cost-effective fabrication, rapid design modifications, and efficient validation of individual components throughout the development process. Figure 4 presents the CAD-designed mechanical components of the developed transmission mechanism and their integration into the assembled prototype.

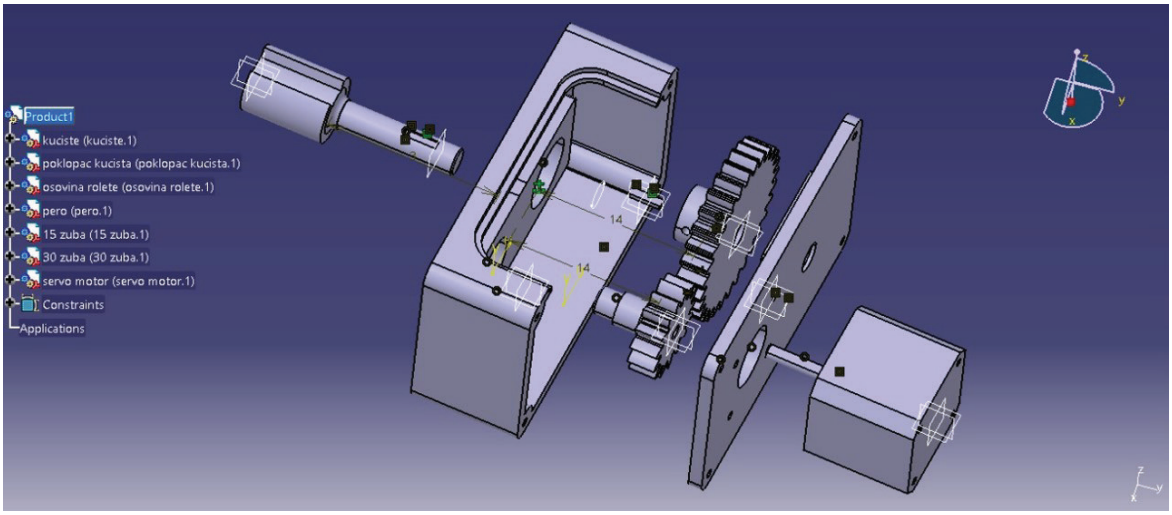


Figure 4: CAD assembly of the mechanical transmission system [6]

4. EXPERIMENTAL VALIDATION AND SYSTEM OPERATION

The developed control system continuously monitors ambient illumination using the BH1750 digital light sensor and automatically adjusts the position of the blinds to maintain a predefined illumination level. Sensor readings are periodically acquired and compared with a reference illumination value. When the measured illumination deviates from the predefined threshold, the

microcontroller generates control signals for the stepper motor, causing the blinds to move in the required direction until the desired lighting conditions are restored.

To ensure reliable operation, an initialization procedure is executed during system startup. The stepper motor first moves the blinds toward a predefined reference position until a limit switch is activated. This position is then stored as the home position and used as a reference for all subsequent movements. The implementation of a limit switch prevents excessive winding of the blinds and contributes to the safe operation of the system.

The control algorithm was intentionally designed to be simple and robust. The measured illumination level is continuously compared with the target value and a predefined tolerance band. If the illumination level falls below the desired range, the blinds are adjusted to admit additional daylight. Conversely, if the measured illumination exceeds the target range, the blinds are repositioned to reduce incoming light. This approach enables automatic adaptation to changing environmental conditions while minimizing unnecessary motor movements.

Experimental validation was performed on the assembled prototype under varying lighting conditions. The first stage of testing focused on verifying the functionality and responsiveness of the BH1750 sensor by exposing it to different illumination levels and monitoring the measured values displayed on the user interface. The sensor demonstrated stable operation and sufficient sensitivity to detect changes in ambient light intensity. Following the sensor validation, the complete mechatronic system was assembled and tested. Particular attention was devoted to the interaction between the sensing, control, and actuation subsystems. The experimental results confirmed that the stepper motor reliably adjusted the blind position according to the measured illumination levels and that the implemented limit switch successfully prevented undesired motion beyond the predefined operating range. The system responded consistently to changing lighting conditions and maintained stable operation throughout the testing process.

The completed prototype used during experimental validation is shown in Figure 5. The obtained results demonstrate the feasibility of implementing a low-cost mechatronic solution for automatic indoor light regulation using widely available electronic components, additive manufacturing technologies, and open-source development platforms.

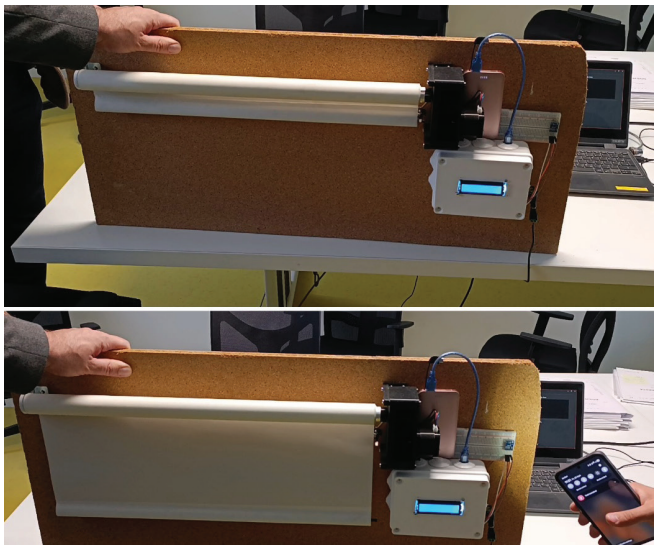


Figure 5: Automatic adjustment of blind position in response to changing light conditions

5. CONCLUSION

This paper presented the development and experimental validation of a low-cost mechatronic system for automatic indoor light control based on ambient illumination measurements. The developed prototype successfully integrates sensing, embedded control, motor actuation, and additive manufacturing technologies into a functional solution capable of automatically regulating blind position in response to changing lighting conditions. Experimental testing confirmed reliable system operation and demonstrated the potential of low-cost automation technologies to improve indoor environmental conditions and support energy-efficient utilization of natural daylight. In addition to its practical application, the developed system represents a suitable educational platform that combines multiple engineering disciplines and aligns with the objectives of the iEduBot project. Future work will focus on wireless communication, enhanced sensing capabilities, and integration into smart building and IoT environments.

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Professional paper

INTEGRATED ACTIVE AND PASSIVE SAFETY ARCHITECTURE OF INDUSTRIAL BELT CONVEYOR SYSTEMS IN COKE HANDLING OPERATIONS

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Abstract: *Belt conveyor systems are essential for continuous material transport in coke processing facilities, where safe operation is critical. This paper analyzes conveyor safety systems at the coke separation plant of ArcelorMittal Zenica, which operates 1,321.5 m of heat-resistant conveyor belts for coke transport. Using operational documentation, workplace risk assessments, and scientific literature, the study examines active and passive safety measures. Active elements include lighting, acoustic warnings, fire detection and suppression, belt slip protection, and rotating part guards, while passive elements include emergency stop buttons, rope pull switches, chute blockage detectors, and belt misalignment controls. The paper emphasizes the importance of the Lockout-Tagout (LOTO) procedure. Focus is placed on critical hazard zones, especially nip points between drums and belts, responsible for 48% of injuries. The paper concludes with recommendations aligned with ISO 22776, EN 620, and CEMA safety standards.*

Keywords: *belt conveyor safety, coke transport, active protection, passive protection, Lockout-Tagout (LOTO) procedure*

1. INTRODUCTION

Belt conveyor systems represent the most widely deployed category of continuous material handling equipment in heavy industry, offering high throughput capacity, mechanical simplicity, and low operating cost per tonne transported. In metallurgical contexts, they are indispensable — forming the arterial infrastructure through which raw materials and intermediate products flow between production stages.

The coke separation plant at ArcelorMittal Zenica operates 1,321.5 m of thermally-resistant conveyor belt infrastructure (rated to 200°C continuous, 400°C peak) across multiple conveyor units (K1–K9+), handling coke that arrives from the ovens at elevated temperatures with heavy dust loads. This creates a demanding safety environment combining generic conveyor hazards with coke-specific risks: fire from incandescent material, dust explosion, and chronic carcinogenic exposure to polycyclic aromatic hydrocarbons (PAHs), classified Group 1 by IARC [1].

This paper provides a systematic analysis of the active and passive safety architecture applied to these systems, contextualizing the facility's approach within international standards and identifying opportunities for enhancement [2][3]. The analysis is further situated within broader Industry 4.0 developments relevant to industrial safety, including predictive maintenance strategies for conveyor systems [13], intelligent sensor-based conveyor condition monitoring [14], and digital occupational safety management technologies [15], which represent complementary directions for future enhancement of the plant's safety architecture.

2. METHODOLOGY

This study adopts a qualitative, document-based analytical approach combining site-specific operational records with a targeted review of scientific and normative literature. Three categories of source material were consulted. First, internal operational documentation of the ArcelorMittal Zenica Coke Separation Plant, equipment specifications, control-system logic diagrams, and maintenance and incident logs, obtained through direct collaboration with plant engineering and safety personnel. Second, the facility's workplace risk assessment, prepared in accordance with applicable Bosnia and Herzegovina occupational safety legislation, which was used to identify and cross-check the hazard zones and injury mechanisms reported in Section 3. Third, peer-reviewed scientific literature and international standards addressing belt conveyor safety, retrieved through targeted searches of Scopus, Web of Science, and standard-issuing body repositories (CEN, ISO, OSHA) using combinations of the keywords “belt conveyor,” “occupational safety,” “nip point,” “Lockout-Tagout,” and “coke handling.” Sources published before 2010 were retained only where they represent foundational statistical or regulatory references without a more recent equivalent.

Each identified safety measure was classified as active or passive according to a single functional criterion: active elements act automatically, without operator intervention, to prevent a hazardous event from occurring (e.g. automated fire suppression, belt slip cut-out), whereas passive elements require a deliberate triggering action by personnel, or reduce the consequences of an event already in progress, without themselves detecting or forecasting the hazard (e.g. emergency stop buttons, rope pull switches). This criterion was applied consistently to resolve borderline cases, such as belt misalignment control, which combines a passive mechanical guide (continuous correction) with an active, sensor-triggered stop (limit switch) and is therefore discussed as a dual-mode system in Section 5.4. The safety architecture identified through this process was then benchmarked against the applicable clauses of EN 620, ISO 22776, EN ISO 13857, and CEMA guidance (Section 8) to derive the recommendations presented in Section 9.

3. HAZARD PROFILE

Occupational injury statistics reveal a consistent pattern of hazard concentration in belt conveyor operations. Nip points between moving belt and rotating drums account for 48% of all conveyor injuries — the converging gap exerts a powerful draw-in force capable of causing degloving, crushing, and amputation before any human reaction is possible. Falls onto conveyors and falling material represent a further 26% [4].

Cleaning activities performed on running conveyors account for 23% of injuries, and maintenance for a further 20% — together representing 43% of all incidents [4][5]. These two categories therefore drive the design priorities for the safety systems analyzed in this paper. Coke-specific hazards add further dimensions: thermal fire risk from incompletely quenched coke, explosive coke dust atmospheres (ATEX zones, 35–2,000 g/m³ ignition range) [6][7], respiratory carcinogen exposure, and high-energy impact from large coke lumps at transfer points.

Table 1. Statistical distribution of conveyor injury locations [4]

Hazard zone	Injury share (%)	Primary mechanism
Nip point: drive/take-up/deflection drum – belt	48%	Entrapment, draw-in
Nip point: carrying/return idler – belt	13%	Entrapment
Fall onto conveyor / material fall from belt	26%	Impact, fall
Other conveyor component zones	13%	Variable

4. ACTIVE SAFETY ELEMENTS

Active safety elements prevent the occurrence of an undesired event before it happens, forming the first line of defense in the safety hierarchy.

4.1. Workspace illumination

Adequate illumination, combining natural light at drum stations with facility-wide LED artificial lighting, enables detection of belt defects, roller misalignment, and structural deterioration during walkthroughs, while preventing slips and falls in enclosed galleries. ArcelorMittal Zenica's LED replacement program improves vibration resistance, service life, and color rendering relative to sodium vapor predecessors. Minimum maintained illuminance of 300–500 lux for inspection tasks is specified by EN 12464-1.

4.2. Acoustic pre-start warning

All conveyors are equipped with electric bells activating 40 seconds before startup, with signals distributed at the drive drum, take-up station, and at intervals along the full belt run. This architecture ensures audible coverage without dead spots. Signal audibility above ambient noise, generated by classification screens, crushers, and ventilation fans, must be periodically verified, and issuance of operating permits is conditioned on confirmed signal functionality.

4.3. Thermographic detection and automated fire suppression

The most technically sophisticated active element is the thermographic detection and automated suppression system at the K1–K2 transfer point. A Raytek ThermoView Pi20 thermal imaging camera (IP54, -40°C to +500°C) provides full radiometric imaging of the coke stream rather than point measurement, enabling spatial detection of hot material [8]. When coke temperature exceeds 300°C, an automated response sequence executes:

- K1 stops immediately; K2 decelerates under frequency converter control with position encoder tracking the hot material location.
- Solenoid valve opens, applying water spray for 30 seconds precisely over the detected hot zone.
- Restart of both conveyors requires positive operator authorization following on-site visual verification, preventing premature resumption with still-incandescent material.

This layered design, automated immediate response plus mandatory human verification, exemplifies sound safety system architecture. Current coverage is limited to the K1–K2 point; extension to all transfer points warrants assessment (see Section 9).

4.4. Belt slip protection

Belt slip, the drive drum rotating faster than the belt moves, generates friction heat capable of igniting belt rubber and causing catastrophic conveyor fires. A speed sensor on a deflection drum (not the drive drum, which continues rotating during slip) measures actual belt speed. When actual speed falls below 80% of commanded speed, the drive motor is immediately de-energized. Correct sensor placement on a non-driven element is fundamental: a drive drum sensor would fail to detect the slip condition. Regular cleaning of sensors is essential in the coke dust environment, as contamination causes erroneous readings [9].

4.5. Rotating part guarding

Metal guards, mesh screens, housings, and shields, provide physical barriers between workers and all rotating components including drive drums, take-up drums, deflection drums, and drive shafts. Compliant guarding per EN ISO 13857 [10] must simultaneously prevent body access to the danger zone, permit lubrication without removal (via extended nipples and hose extensions), resist abrasion and corrosion, and introduce no new hazards. Engineering guards for legitimate tool-free access during LOTO maintenance directly addresses the most common driver of guard removal [9].

5. PASSIVE SAFETY ELEMENTS

Passive safety elements limit the consequences of an undesired event that is already occurring, relying on simple triggering mechanisms accessible to any worker without requiring automated detection logic.

5.1. Emergency stop push buttons

Mushroom-head emergency stop switches are positioned at defined intervals along the ramp worker's path, ensuring a stop device is always within reach. The large actuator, operable with a closed fist, locks in the depressed position, providing visible stop status indication and requiring deliberate reset. Restart is only possible after cause identification and control room notification, creating a mandatory investigation checkpoint.

5.2. Rope pull emergency stops

Rope pull switches extend emergency stop coverage to the full length of each conveyor (all except K7, 21 m, manual operation) along both sides, eliminating blind spots. Any worker at any position can initiate an immediate stop. The electrical behaviour, maintaining the conveyor without power until deliberate control room reset, prevents restart while personnel may still be adjacent to the belt. Critically, rope pull activation is not energy isolation; LOTO procedure remains required for any maintenance contact.

5.3. Chute blockage detection

Transfer chute blockages are operationally common in coke handling. A switch actuator mounted against a rubber pad on the external chute wall detects the elastic deflection caused by material pressure when blockage occurs, immediately de-energizing the feeding conveyor. Manual reset after physical chute clearing provides a physical interlock preventing restart with a blocked chute. Beyond safety, early blockage detection limits material spillage and drive train overload, aligning safety with operational continuity.

5.4. Belt misalignment control

Two complementary devices address lateral belt displacement. Vertical metal guide rollers installed on both sides near drums and at run intervals passively deflect the belt edge back toward center for minor transient misalignment without production interruption. Limit switch sensors de-energize the conveyor when displacement reaches an unacceptable level, preventing structural contact and belt edge damage. Restart requires manual reset after cause identification. The combination of passive correction and active stop implements a proportionate layered response: continuous correction of minor deviations, definitive stop for severe events.

6. LOCKOUT-TAGOUT (LOTO) PROCEDURE

LOTO, designated in facility documentation, is the foundational safety control for all maintenance and servicing activities, eliminating the risk of unexpected energization during work. It is mandated by OSHA 29 CFR 1910.147 [11], the EU Machinery Directive, and applicable BiH occupational safety legislation.

The procedure at the Coke Separation Plant employs a personal padlock lockbox system:

- Shift supervisor issues a formal isolation request; a competent person isolates and locks the energy source, attaching an identifying tag.

- The single master key (no duplicate) is placed in a portable lockbox, which is then locked by the personal padlock of every worker participating in the maintenance activity, including the supervisor.
- The supervisor issues a written work permit; the lockbox travels to the work site, making master key retrieval physically impossible while workers are present.
- Each worker removes their padlock upon completing their tasks; the supervisor removes theirs last, confirming work completion before authorizing energy restoration.

This design ensures no single individual controls both work and energy isolation; every participating worker has individually confirmed their own safety before power restoration; and the physical lockbox provides an unambiguous visible representation of isolation status. LOTO applies to all maintenance activities: belt splicing, idler replacement, drum maintenance, scraper adjustment, sensor calibration, and structural repair.

7. AUTOMATION AND CONTROL INTEGRATION

Full system automation integrates all safety elements into a coherent operational architecture. Sequential startup (downstream first) and shutdown (reverse sequence, belts run empty) prevent material accumulation and full-belt restarts. Cascade shutdown automatically stops all upstream conveyors when any unit stops due to fault, limiting disturbance extent. Pre-start acoustic signaling is integrated into the startup sequence, ensuring it always precedes belt movement. All faults are registered at the central dispatch panel with fault type and location identification.

The control room visualization system (vizualizacija separacije koksa) provides the dispatcher with a real-time graphical system overview overlaid with sensor data including the thermal camera feed, enabling effective incident management across the multi-conveyor system.

8. APPLICABLE STANDARDS

The safety architecture implemented at the Coke Separation Plant is aligned with a range of international standards and industry guidelines governing conveyor design, guarding, electrical safety, and operation in hazardous environments.

Table 2. Applicable international standards

Standard	Scope	Primary Relevance
EN 620:2002+A1:2010	Safety requirements for fixed belt conveyors	Primary design/guarding standard
ISO 22776:2021	Safety requirements for belt conveyors	International benchmark
EN ISO 13857:2019	Safety distances – nip point guarding	Guard dimensions and opening sizes

9. RECOMMENDATIONS

Based on the analysis of current systems against international standards and best practice, the following priority recommendations are proposed:

- ATEX compliance assessment: Conduct formal zone classification for all areas where coke dust can accumulate or become airborne, and verify all installed electrical equipment meets the required ATEX category. This is a legal requirement and represents a potentially critical compliance gap.
- Thermographic coverage extension: Perform a risk assessment for hot coke entry at all transfer points beyond K1–K2, and install additional detection at any identified locations. A single camera covering one transfer point leaves upstream and downstream points unmonitored.
- Predictive bearing maintenance: Implement vibration monitoring for idler roller bearings to enable planned replacement before seizure, eliminating the acute friction-fire hazard from failed rollers while reducing unplanned downtime.
- Belt cover thickness monitoring: Replace visual-only belt condition assessment with non-contact thickness measurement, enabling objective replacement scheduling based on remaining material rather than elapsed time.
- Acoustic signal verification: Verify pre-start signal audibility at all worker positions against measured ambient noise levels; document results and include re-verification in the periodic safety audit program.
- LOTO training formalization: Establish a documented LOTO training and re-certification program (maximum 2-year intervals) for all personnel who authorize, perform, or supervise maintenance on conveyor equipment.

10. CONCLUSIONS

The belt conveyor safety architecture at the ArcelorMittal Zenica Coke Separation Plant represents a multi-layered approach that aligns with international safety engineering principles. Particular strengths include the thermographic detection and automated suppression system, providing faster and more precise response to incandescent coke than any manual intervention, comprehensive bilateral rope pull coverage on all major conveyors, integrated cascade shutdown automation, and the structured personal-padlock LOTO procedure. Priority areas for enhancement are ATEX compliance verification for coke dust zones, extension of thermographic coverage beyond the K1–K2 transfer point, and introduction of systematic bearing condition and belt thickness monitoring. A critical observation throughout this analysis is the strong alignment between safety improvement and operational continuity: the systems that most effectively prevent conveyor fires and belt failures are the same systems that protect production uptime [12]. Investment in the recommended enhancements therefore generates concurrent returns in reduced incident frequency and improved operational reliability, making the safety case simultaneously an economic case for the facility's blast furnace supply chain.

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DIGITIZATION OF TEXTILE MATERIALS FOR HGSS PROTECTIVE CLOTHING

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Abstract: *This study investigates the application of artificial intelligence for the digitization of textile materials used in protective clothing for the Croatian Mountain Rescue Service (HGSS). Three flame-resistant woven fabrics were physically characterized by measuring thickness and mass per unit area and subsequently digitized using the SEDDI Textura platform. AI-generated visual (PBR texture maps) and mechanical parameters were implemented in the CLO3D environment to evaluate their suitability for virtual garment development. The generated digital materials accurately reproduced the visual appearance and simulated mechanical behavior of the physical fabrics, demonstrating good agreement with their measured properties.*

Keywords: *protective clothing; textile material digitization; AI; SEDDI Textura; virtual prototyping*

1. INTRODUCTION

Protective clothing represents a critical component of personal protective equipment for emergency responders operating in hazardous environments. In the case of wildfire interventions, protective garments must provide an appropriate balance between thermal protection, mechanical durability, comfort, and mobility [1,2]. Members of the Croatian Mountain Rescue Service (HGSS) are frequently involved in rescue operations and support activities during wildfire events, often under conditions of elevated temperatures, intense physical activity, and prolonged exposure to environmental hazards. Consequently, the selection and development of suitable textile materials for protective clothing is of particular importance.

Recent advances in digital product development technologies have significantly transformed the textile and apparel industry. The increasing adoption of virtual prototyping, three-dimensional (3D) garment simulation, and digital twins enables manufacturers to reduce development time, decrease the number of physical samples, and improve communication throughout the supply chain. The accuracy of such digital processes largely depends on the quality of digital textile material models, which must realistically represent both the visual appearance and mechanical behavior of real fabrics [3].

Traditional methods of textile material characterization for virtual simulation often require extensive laboratory testing and manual parameter adjustment within 3D simulation software. To overcome these limitations, artificial intelligence (AI) technologies have recently been introduced into the textile digitization process. AI-based platforms can generate digital material models from scanned fabric images combined with a limited set of physical input parameters, providing a faster and more accessible approach to material digitalization. One of the emerging solutions in this field is the SEDDI Textura platform, which utilizes artificial intelligence algorithms to generate physically based rendering (PBR) texture maps and material simulation parameters suitable for implementation in virtual garment development systems [4]. Such technologies have the potential to support the development of advanced protective clothing by enabling rapid evaluation of material behavior in a digital environment before the production of physical prototypes.

The aim of this research was to investigate the applicability of AI-assisted textile material digitization for the development of HGSS protective clothing intended for wildfire interventions. Three flame-resistant woven fabrics used to produce protective garments were characterized through experimental determination of thickness and mass per unit area. Subsequently, the materials were digitized using the SEDDI Textura platform, and the generated visual and mechanical parameters were analyzed regarding their suitability for implementation in 3D garment simulation environments.

2. MATERIALS AND METHODS

2.1. Characterization of textile materials for HGSS protective clothing system

The fabrics for protective clothing system analyzed in this study was developed for members of the Croatian Mountain Rescue Service (HGSS) participating in wildfire intervention and rescue operations. The garment system was designed to provide an optimal balance between thermal protection, mechanical resistance, ergonomic performance, and wearer comfort during prolonged exposure to demanding environmental conditions. The clothing ensemble consists of a jacket and trousers manufactured from flame-resistant woven fabrics specifically selected for use in protective apparel. Three fabric samples (F1, F2 and F3) were selected for the research, in accordance with the requirements prescribed by the HRN EN 15614:2008 standard, which defines the requirements for the properties of materials and protective clothing intended for use in outdoor fires, and in accordance with the EN 1149-5:2018 standard, which prescribes the requirements for antistatic properties of materials and design [5,6]. F1 represented an alternative base fabric considered during the development phase of the garment system, while F2 and F3 were incorporated into the final clothing design. F2 was used for reinforcement zones exposed to increased mechanical stress, such as knees, elbows, and shoulder areas, whereas F3 was used as the base fabric for the main garment parts.

All analyzed materials were twill woven fabrics with inherent flame-resistant properties obtained using high-performance fibres. The alternative fabric (F1) consisted of 57% Kermel®, 40% flame-retardant viscose, 2% elastane, and 1% antistatic fibres. The reinforcement fabric (F2) was composed of 93% meta-aramid, 5% para-aramid, and 2% antistatic fibres. The primary garment fabric (F3) contained 64% flame-retardant viscose, 30% meta-aramid, 5% para-aramid, and 1% antistatic fibres, Table 1.

Table 1: Characterization of the fabrics selected for the study

Fabric	Composition	Wave	Weight [g/m2]	Thickness [mm]
F1	57% kermel 40% viscose FR 2% elastane 1% antistatic	Twill	240.94	0.49
F2	93% m-aramid 5% p-aramid 2% antistatic	Twill	221.17	0.42
F3	64% viscose FR 30% m-aramid 5% p-aramid 1% antistatic	Twill	230.07	0.39

The declared mass per unit area of the investigated fabrics ranged from 220 to 230 g/m². These materials were selected due to their favorable combination of flame resistance, thermal stability, mechanical durability, and physiological comfort, which are essential requirements for protective clothing used in wildfire environments. The higher aramid content of the reinforcement fabric provides improved resistance to abrasion and mechanical damage, while the viscose-containing primary fabric contributes to enhanced moisture management and wearer comfort during intensive physical activity. To obtain the input parameters required for textile material digitization, physical characterization of the fabrics was performed through measurements of thickness and mass per unit area, Table 1.

The physical characterization of textile materials was performed to obtain the input parameters required for subsequent AI-based material digitization and virtual garment simulation. The mass per unit area (i.e., specific mass) and thickness of the fabric samples were determined according to the applicable standards, Table 1. The specific weight of fabrics was tested in accordance with the standard HRN EN ISO 3801:2003 - Textiles - Fabrics - Determination of mass per unit length and mass per unit area (ISO 3801:1977), and the thickness was tested in accordance with the standard HRN EN ISO 5084:2003 - Textiles - Determination of thickness of textiles and textile products (ISO 5084:2003:1996).

2.2. AI-based fabric digitization and characterization

The digitization of three selected textile materials was performed using the AI-based platform SEDDI Textura [4]. Prior to the digitization process, fabric samples were prepared to ensure representative visual appearance and surface quality. Samples were free from visible defects, contamination, wrinkles, and mechanical damage. Subsequently, the materials were scanned using a high-resolution flatbed scanner to obtain digital images suitable for further processing. The scanned fabric images were uploaded to the SEDDI Textura platform, where digital material generation was carried out using artificial intelligence algorithms. In addition to the scanned images, experimentally determined physical properties (thickness and mass per unit area), were entered as input parameters. Information regarding fabric construction, weave type, and fibre composition was also provided to improve the accuracy of material characterization.

After defining the required parameters, the platform automatically generated digital textile materials containing both visual and mechanical properties. The generated visual data included physically based rendering (PBR) texture maps, such as albedo, normal, displacement, roughness,

and opacity maps, which are used to reproduce the appearance and surface characteristics of textile materials in virtual environments. These texture maps enable realistic simulation of colour, surface relief, transparency, and light reflection behaviour, Figure 1.

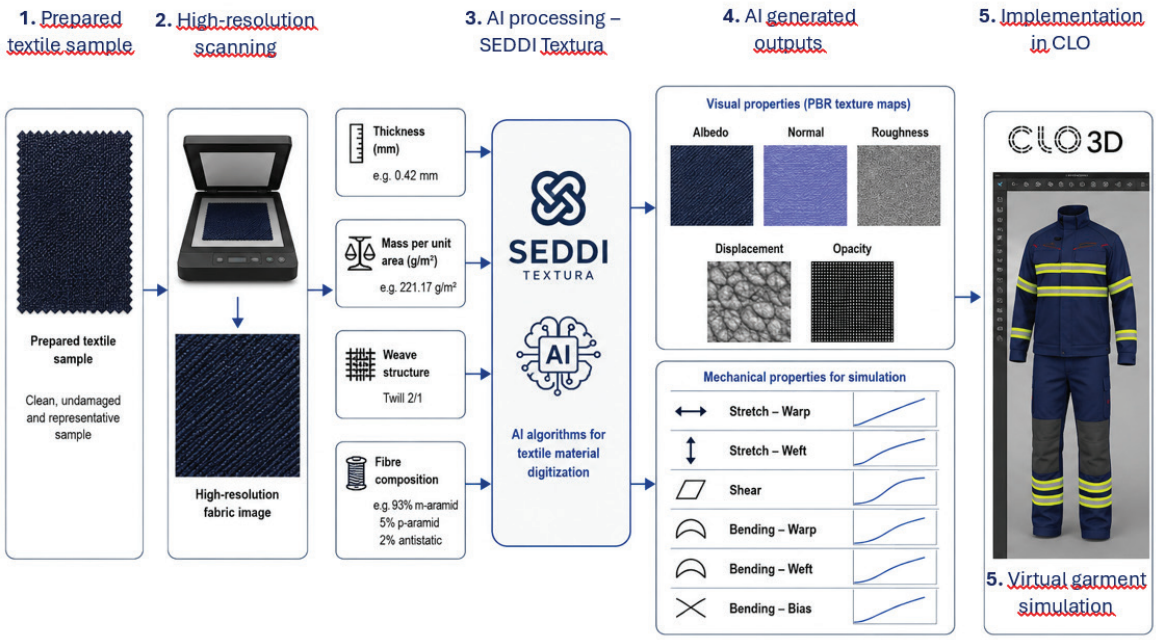


Figure 1: AI-based workflow for textile material digitization using the SEDDI Textura platform and implementation of generated material properties in the CLO3D virtual garment simulation

In addition to visual properties, SEDDI Textura generated a set of mechanical simulation parameters required for virtual garment development. These parameters included tensile behavior in warp and weft directions (Stretch – Warp and Stretch – Weft), shear stiffness (Shear), bending rigidity in warp and weft directions (Bending – Warp and Bending – Weft), and bias-direction bending behavior (Bending – Bias). The generated parameters were exported together with the texture maps and prepared for implementation within the CLO3D garment simulation environment.

Also, a visual comparison between the physical fabric samples and the digital materials generated using the SEDDI Textura platform was performed to evaluate the quality of the digitization process. The comparison included scanned fabric images, the corresponding digital materials, and their 3D simulations in CLO3D. The resulting digital materials were subsequently used for analyzing the applicability of AI-generated textile materials in the virtual development of protective clothing intended for wildfire intervention operations.

3. RESULTS AND DISCUSSION

3.1. Physical characterization of fabrics used in the HGSS protective clothing system

The results revealed measurable differences among the fabrics analyzed. F1 exhibited the highest average thickness (0.49 mm) and the highest mass per unit area (240.94 g/m²). F2, intended for reinforcement zones, showed an average thickness of 0.42 mm and a mass per unit area of 221.17

g/m². The primary garment fabric (F3) demonstrated the lowest thickness value (0.39 mm) and an average mass per unit area of 230.07 g/m². The relatively small differences in thickness among the investigated materials indicate good compatibility within the protective clothing system, while the differences in mass and fibre composition reflect their specific functional roles. The lighter and thinner primary fabric contributes to improved mobility, breathability, and physiological comfort, whereas the reinforcement fabric provides enhanced dimensional stability and resistance to mechanical stress.

3.2. Determining mechanical property parameters using the SEDDI Textura AI application

The experimentally determined thickness and mass per unit area served as input parameters for AI-assisted textile digitization using the SEDDI Textura platform. Although only small differences in physical properties were observed among the analyzed fabrics, the mechanical parameters generated revealed clear distinctions in their simulated behavior, Table 2.

Table 2: Parameter values of the mechanical properties for three basic textile materials for HGSS uniform (F1, F2 and F3) determined by using the SEDDI Textura AI application

Mechanical properties	Fabric		
	F1	F2	F3
Stretch-Warp [g/s²]	661,892	704,384	683,911
Stretch-Weft [g/s²]	394,972	497,904	472,815
Shear [g/s²]	59,998	64,046	52,819
Bending-Warp [gmm²/s²]	23,259	17,216	17,616
Bending-Weft [gmm²/s²]	13,035	15,754	12,689
Bending-Bias [gmm²/s²]	16,868	16,328	14,413

The values of the generated parameters of the stress in the warp direction (Stretch – Warp) and the stress in the weft direction (Stretch – Weft) show differences in the behavior of the material when stretched in the warp and weft directions. In all three samples, higher values were recorded in the warp direction (Warp), which indicates a greater resistance of the material to deformation in the longitudinal direction compared to the transverse direction. Such behavior is characteristic of fabrics in which the arrangement of threads and the structure of the weaves contribute to greater stability in the warp direction.

Sample F2, intended for reinforcement zones of the protective garment, exhibited the highest resistance to tensile deformation in both warp and weft directions as well as the highest shear stiffness. These characteristics indicate superior dimensional stability and increased resistance to deformation under mechanical loading, which can be attributed to its high aramid fibre content.

Sample F1 demonstrated the greatest bending rigidity in the warp direction, suggesting increased resistance to flexural deformation. In contrast, sample F3 showed the lowest bending rigidity, including the lowest bias bending value, indicating greater flexibility and improved drape behavior during virtual garment simulation.

The differences between the parameters found indicate that the SEDDI Textura platform generates different mechanical behaviors of digitized materials depending on their entered physical properties, structure, and raw material composition.

3.3. Results of fabric visual property generation

The digitization process performed using the SEDDI Textura platform generated the PBR texture maps required for realistic 3D visualization of textile materials, including Albedo, Displacement, Alpha, Normal, Roughness, and Specular maps (Figure 1). Together, these maps define the color, surface geometry, transparency, texture details, and light reflection characteristics of digital materials.

The Albedo maps revealed differences in the color and weave appearance of the analyzed fabrics. The Displacement and Normal maps accurately reproduced the surface relief and twill weave structure, while the Roughness maps indicated predominantly matte surfaces with limited light reflection, consistent with the visual characteristics of technical fabrics used for protective clothing. Since all analyzed materials were opaque, the Alpha maps showed no significant differences between the samples and had no noticeable influence on the final visual appearance. Although the platform also generated Specular maps, they were not used in the subsequent CLO3D workflow because the current software version defines material reflectance using the Roughness parameter within the physically based rendering (PBR) system.

Overall, the generated texture maps enabled successful transfer of the visual properties of the analyzed fabrics into the CLO3D environment, resulting in digital materials with a realistic appearance comparable to the original textile samples.

3.4. Results of 3D fabric simulation and comparison with physical samples

The digital materials successfully reproduced the main visual characteristics of the physical fabrics, including the twill weave structure and surface texture. Minor differences were observed in color, light reflection, and the intensity of surface details, which can be attributed to differences between scanned 2D images and the rendering process of digital materials.

To evaluate material behavior during simulation, circular fabric samples were simulated over a spherical object in the CLO3D environment, Figure 2. This enabled visual assessment of flexibility, fold formation, and deformation behavior. The simulated materials exhibited generally similar drape behavior, confirming their compatibility for use within the same protective garment system. However, subtle differences corresponded well with their measured physical and AI-generated mechanical properties. Sample F2 retained a slightly larger and more stable drape profile, consistent with its highest shear stiffness (64,046) and tensile resistance in the warp direction (Stretch–Warp: 704,384), supporting its application in reinforcement areas. Sample F3 adapted more closely to the sphere, reflecting its lower bias bending rigidity (Bending–Bias: 14,413). Sample F1 showed pronounced bending in one direction, corresponding to its high warp bending rigidity (Bending–Warp: 23,259). Overall, the visual analysis confirmed that all three fabrics behave as relatively stiff materials with stable structural characteristics suitable for protective clothing.

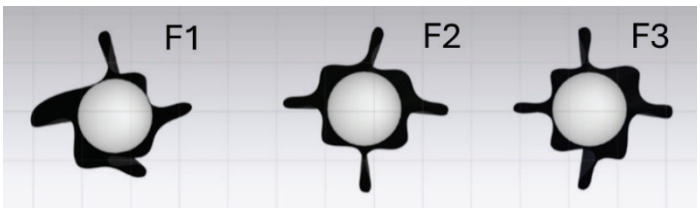


Figure 2: Simulation of drape behaviour of digitized fabrics in the CLO environment (bottom view)

The results demonstrate that textile materials digitized using SEDDI Textura provide a visually and functionally realistic representation of fabric behavior in a 3D environment, while preserving the relationship between the digital models and the physical properties of the original materials.

4. CONCLUSION

The analysis of the results confirms that the physical properties of the investigated materials satisfy the requirements for protective clothing used in wildfire interventions. The primary garment fabric, characterized by lower thickness and mass per unit area, contributes to reduced garment weight, improved wearer mobility, and enhanced breathability and moisture management during prolonged physical activity under elevated thermal loads. In contrast, the reinforcement fabric, with its higher aramid content and more stable structure, provides increased resistance to abrasion, wear, and thermal stress in areas exposed to intensive mechanical loading, such as the knees, elbows, and shoulders. The combination of these materials achieves an effective balance between protection, durability, and ergonomic performance required for HGSS protective clothing.

AI-based textile material digitization using the SEDDI Textura platform complements conventional laboratory characterization methods by enabling rapid generation of digital material models from a limited set of physical input parameters. Although laboratory systems such as the Kawabata Evaluation System (KES) provide highly accurate standardized measurements, they require specialized equipment and considerable time and resources. In contrast, SEDDI Textura offers a faster and more accessible workflow for generating digital materials suitable for 3D garment simulation. The generated visual and mechanical properties facilitate virtual prototyping, reduce the need for physical samples, shorten product development cycles, and support the digital transformation of the apparel industry through more efficient and sustainable product development.

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Professional paper

SAFETY CHALLENGES IN MAINTENANCE OF ELECTRIC AND HYBRID VEHICLES

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Abstract: *Over the past three decades, the automotive industry has seen a major technological leap in the development of electric and hybrid vehicles, as a result of efforts to use energy more efficiently in transportation and consequently reduce emissions caused by fossil fuels. New technologies in these vehicles also pose new safety challenges, both for workers in specialized services and for safety and protection engineers involved in developing risk assessments for these workplaces. The theoretical part of the paper describes the types of electric and hybrid vehicles and their high-voltage components, which can pose a danger to workers who service them. It also discusses the legal regulations related to the work of electric and hybrid vehicle service technicians. In the experimental part of the work, risk assessments were reviewed in seven specialized services, and it was determined which worker protection measures were prescribed and how their protection could be improved.*

Keywords: *electric vehicles, hybrid vehicles, safety and protection, legal regulations, risk assessment.*

1. INTRODUCTION

Over the past three decades, efforts have been made globally to reduce the use of fossil fuels in the transport sector. Yet, consumption continues to grow due to the increasing number of vehicles and the greater distance they travel. Transport is the only sector in which greenhouse gas emissions have increased over the past three decades, rising by 33.5% between 1990 and 2019 [1]. The application of sustainable development principles in this sector has given new impetus to the development of electric and hybrid vehicles, and car manufacturers now offer models that increasingly compete with conventionally powered vehicles. Electric and hybrid vehicles have propulsion systems with operating voltages between 150 and 800 V, with 400 V systems being the most common. Regulation No. 100 Rev. 3 of the United Nations Economic Commission for Europe defines high voltage for direct current in electric vehicles as a voltage greater than 60 V and less than or equal to 1500 V. For alternating current as a voltage greater than 30 V and less than or

equal to 1000 V. With the emergence of high voltage in cars, new hazards have also appeared for workers in specialized service workshops through direct or indirect contact with live components. This situation also represents a new safety challenge for safety and protection engineers involved in preparing risk assessments for these workplaces; therefore, this paper will demonstrate how effectively they can meet these new challenges.

1.1. Types of electric vehicles

Electric vehicles are classified according to their power sources, which may come from high-voltage batteries in battery electric vehicles (BEVs), or from combined power sources consisting of an internal combustion engine and a hybrid battery in hybrid electric vehicles (HEVs).

Battery electric vehicles store electrical energy in high-voltage batteries that are charged from an external power source. At the same time, additional charging is also possible during driving through the built-in regenerative braking system. Compared with a conventional vehicle, the advantages of an electric vehicle include high energy efficiency, direct power transmission to the drive wheels, and a simpler structure. Figure 1 shows the main components of an electric vehicle.

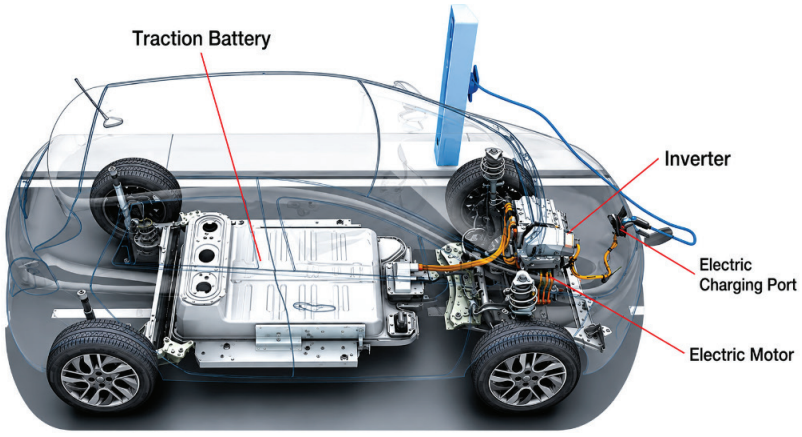


Figure 1: Main components of an electric vehicle [2]

Hybrid electric vehicles have, in addition to a conventional engine, an electric motor powered by a high-voltage battery. The high-voltage battery in hybrid vehicles has a smaller capacity, allowing the vehicle to be started by the electric motor and driven over shorter distances, after which the power required to move the vehicle comes from the internal combustion engine (ICE). Depending on their design, hybrid vehicles are divided into mild hybrid electric vehicles (MHEVs), full hybrid electric vehicles (FHEVs), and plug-in hybrid electric vehicles (PHEVs).

1.2. High-voltage components as a source of danger

The danger posed by electrical energy depends on the current that flows when a worker comes into contact with live parts due to damaged electrical equipment or a fault in the electrical circuit [3]. By the term "live work" in this paper, we mean the so-called "live-line work" or "hotline work". One form of contact is the occurrence of an electric arc, in which continuous electrical energy is discharged through a mixture of gases or air. Electric current can cause thermal, mechanical, chemical, or biological injuries to the body and, in certain cases, the death of a worker [4]. Because of the high-voltage components installed in electric and hybrid vehicles, careless and unprofessional work on such vehicles may cause life-threatening injuries to workers.

The main source of danger, from which the assessment always begins, is the high-voltage battery. It stores energy in chemical form and converts it to electrical energy when needed to power the motor and other vehicle components. In principle, batteries consist of a series of cells, each containing a positive electrode (cathode), a negative electrode (anode), and an electrolyte that allows the transfer of ions between the electrodes. This chemical reaction process during battery charging and discharging enables energy to be stored and released [5]. Faults in the high-voltage battery and improper handling during service procedures are the main sources of danger when working with it. Any mechanical damage to the battery may cause a short circuit inside it, leading to overheating and fire, or to the formation of an electric arc.

High-voltage conductors are the next component that poses a major danger. Their role is to transmit electrical energy from the high-voltage battery to the electric motor and other high-voltage components of the vehicle. Their outer insulating layer is characteristically orange, making it easier to distinguish from the low-voltage installation. Damage to the conductors may cause electric shock, fire, or explosion.

Among other high-voltage parts that may pose a danger, the on-board charger (OBC), power distribution unit (PDU), DC/AC converter, DC/DC converter, air-conditioning compressor, and the high-voltage motor used to drive the vehicle should be highlighted. Failure or improper handling of any component may pose a hazard to workers in specialized service workshops.

1.3. Legal regulations related to work on electric and hybrid vehicles

At the European Union level, there is no directive specifically addressing the maintenance of electric and hybrid vehicles, and at the national level, there is no separate regulation that legally governs this area of occupational safety. This legal gap is covered by manufacturers' service instructions and standard regulations governing the protection of workers who work with high voltage. In addition to the Occupational Safety Act (Official Gazette 71/2014, 118/2014, 94/2018, 96/2018), the Regulation on the Preparation of Risk Assessments (Official Gazette 112/2014, 129/2019), the Regulation on Occupational Safety for Workplaces (Official Gazette 105/2020), and others, workers are primarily protected by the Regulation on Jobs with Special Working Conditions (Official Gazette 05/1984) and the Regulation on Safety and Health at Work with Electrical Energy (Official Gazette 88/2012).

The Regulation on Jobs with Special Working Conditions specifies which jobs are considered special working conditions and the requirements that workers in those jobs must meet. These requirements relate to the worker's age, sex, professional and psychological ability, and health status. The regulation classifies the installation, maintenance, and testing of electrical installations and devices above 250 V and 220 V with special requirements as jobs with special working conditions. Since the battery voltages of electric and hybrid vehicles exceed the stated values, the work of workers in specialized service workshops is characterized by special working conditions. Workers must also meet special requirements relating to age, professional ability, health status, and psychological ability. The worker must be an adult with appropriate qualifications to acquire the knowledge, skills, work ability, and habits required to perform the job. Professional competence means the worker is trained to apply “S” protection, while health status requires good eyesight and color discrimination. The requirements for psychological ability are general intellectual development and emotional stability above the lower limit of average. The regulation defines that health status and psychological ability must be checked every 48 months.

The Regulation on Safety and Health at Work with Electrical Energy was primarily written to regulate work on or near electrical structures, electrical plants, electrical lines, electrical installations, and equipment, in accordance with Croatian standards from the HRN EN 50110 series. Nevertheless, it also defines the obligation to apply it to work with electrical energy in other workplaces where it is used. Safety and health rules must be applied to electrical plants, installations, and equipment using alternating current of industrial frequency with nominal voltages greater than 50 V up to the highest voltages, direct current with nominal voltages greater than 120 V up to the highest voltages, and also to lower voltages if prescribed by a special regulation or rulebook. This Regulation does not apply to electrical plants, installations, and equipment on, for example, self-propelled aircraft and flying vehicles, seagoing vessels with their own propulsion and under the command of a captain, railway traction systems, or motor vehicles; however, point 2 of Article 4 defines that the Regulation also applies to them if there is no special regulation on safety and health at work with electrical energy. Accordingly, the stated regulation must also be applied in specialized service workshops for electric and hybrid vehicles. In workplaces, danger zones must be identified and marked. Danger zones are divided into three zones. The first zone is the free-movement zone, in which all workers trained for safe work and service visitors accompanied by an authorized person may move. In the second zone, the approach zone, appropriate protective measures must be used during movement and work. The third zone is the live-working zone. In this zone, the worker must take all measures to protect against direct and indirect contact with a voltage source. It is important to observe the protective distance (Dz) of 500 mm for work within 1000 V of an unprotected voltage source, and the safety distance (DS) of 1000 mm for non-electrical work. Figure 2 shows an example of demarcation of the working area.

The Regulation also defines that insulated tools and insulated tools for live work are used in the approach zone and in the live-working zone. The use of protective devices is also prescribed for workplaces, such as insulating rods, insulating covers, insulating plates, earthing and short-circuiting devices, barriers, fences, flags, measuring instruments and voltage indicators, and other protective equipment. Depending on the type of hazard, the use of personal protective equipment for work on electrical installations is prescribed by a specific regulation. Personal protective equipment for work on, with, or near electrical plants and installations includes: insulating gloves, insulating boots and overshoes, safety goggles and an eye protection shield, an insulating safety helmet, protective clothing, safety footwear, protective gloves, gas masks, and other personal protective equipment [7].

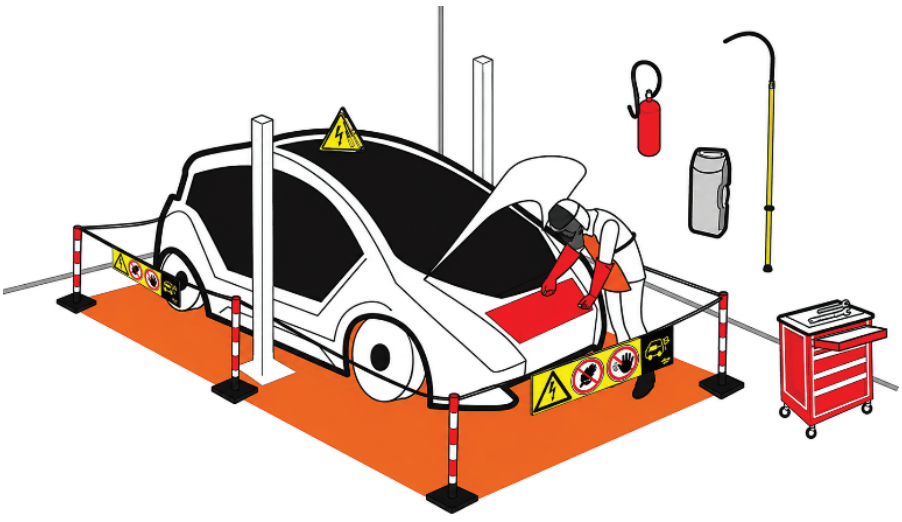


Figure 2: Delimitation of the working area [6]

Tools, protective devices, and personal protective equipment must be manufactured in accordance with regulations and Croatian standards, and if there is no Croatian regulation or standard, they must be manufactured in accordance with European or international standards [8]. All workplace tools, as well as personal protective equipment, must include the manufacturer's instructions for use in Croatian. Wearing an insulating helmet is prescribed in all danger zones. Before starting work in a de-energized state, the workplace must be secured by applying the “five safety rules” in the following order: disconnect and isolate from voltage, prevent reconnection, verify the absence of voltage, earth and short-circuit, and fence off the workplace from live parts [7]. Article 86 of the Regulation is important for application in service workshops because it prescribes which work may be performed live. Among other things, it defines the performance of work at a nominal voltage of up to 1 kV (including incorrect indications in auxiliary circuits, fault-finding work, functional testing of apparatus and assemblies, and checking and commissioning). The same article prescribes that the worker performing such work must be trained at authorized educational institutions.

Live work requires the use of prescribed and verified working methods, namely: working at a distance from live conductors, working with insulating gloves, and working at conductor potential [7]. Work may be performed only by electrical professionals or by persons instructed in electrical engineering. Under point 4.2, the Regulation defines training for work with high-voltage systems; therefore, all workers who service electric and hybrid vehicles must receive additional professional training for this. Depending on the type of work, workers must be instructed and trained under conditions equivalent to actual work and must also be specifically trained for the specific work. A special training program must be established to develop and maintain the abilities of competent and instructed persons to perform live work. Such a program must meet the special requirements of live work and should be based on theoretical and practical tasks. These tasks and exercises should be typical of the work to be performed after the instruction, or if they differ from such work, they should be based on the same safety principles. Training programs for live work are established by an appropriate institution for training workers for live work [7]. This training is essential for the safe and efficient servicing and maintenance of battery systems under voltage, which are key components of the new generation of vehicles and affect their efficiency and longevity [9]. The Regulation on Safety and Health at Work with Electrical Energy prescribes the periodic renewal of authorizations for live work. Its validity should be checked in the following cases: reassignment of personnel, change of tasks, prolonged interruption of activity, health restrictions, reported non-compliance with work instructions, significant changes to plants (changes in operating resources or in construction), changes in the working method, or changes in the method of putting into operation [7].

2. RESEARCH METHODS

In the practical part of the paper, field research was conducted in service workshops that service electric and hybrid vehicles in addition to conventional vehicles. In the period from 17 July 2025 to 7 May 2026, a total of eleven service workshops were visited; however, by the time the paper was written, seven of them had expressed interest in participating anonymously in the research. The visit consisted of interviews with service managers, directors, or persons responsible for occupational safety within the companies. After approval by the legal departments of the service workshops participating in the research, the risk assessments for the workplaces of electric and hybrid vehicle service technicians were reviewed, and in three service workshops visits during service procedures were also permitted.

3. RESULTS

Based on the review of risk assessments in nine service workshops, Table 1 shows which of the protective equipment prescribed by the Regulation on Safety and Health at Work with Electrical Energy was prescribed in the reviewed risk assessments of the service workshops. For reasons of anonymity, which was one of the conditions of the research, the service workshops were designated in sequence from "W-1" to "W-9".

Table 1: Prescribed personal protective equipment in service workshops

Personal protective equipment	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9
Insulating gloves			YES	YES	YES	YES	YES	YES	YES
Insulating boots and overshoes									
Safety goggles and eye protection shield		YES	YES	YES	YES	YES	YES	YES	YES
Insulating safety helmet									
Protective clothing	YES	YES	YES	YES	YES	YES	YES	YES	YES
Safety footwear	YES	YES	YES	YES	YES	YES	YES	YES	YES
Protective gloves	YES	YES	YES	YES	YES	YES	YES	YES	YES
Gas masks		YES							
Other personal protective equipment			YES	YES	YES	YES	YES	YES	YES

4. DISCUSSION

After reviewing the research results, it was observed that in two service workshops (W-1 and W-2), hazards related to the harmful effects of electrical energy had not been recognized, because none of the insulating personal protective equipment was prescribed in the risk assessment. This represents slightly more than one fifth of the risk assessments with an unrecognized hazard out of the total number of assessed risk assessments, which is not a negligible figure from a statistical point of view. In Workshop W-1, protective clothing, footwear, and gloves were prescribed as protection against mechanical damage, while the hazard of exposure to high voltage was disregarded. In Workshop W-2, the situation can be described as similar, but protection of the eyes and respiratory organs was added. The assessment prescribed an FFP3 mask as protection against dust, aerosols, and viruses. Since the assessment was prepared during the "COVID period", it may be assumed that it was included as a consequence of compliance with health measures during the outbreak of the SARS-CoV-2 virus. In the remaining seven service workshops, the assessments were prepared more thoroughly, with recognition of the hazards related to the harmful effects of electrical energy; however, none of the risk assessments contained a list of all the equipment prescribed by the Regulation. The research results present the situation in the prepared risk assessments, but the actual situation would have been more precisely expressed if a larger number of specialized service workshops had responded to the study.

5. CONCLUSION

The maintenance and repair of electric and hybrid vehicles cannot be considered a routine working procedure as is the case with vehicles with internal combustion engines, because work with the high-voltage battery and other high-voltage components is unavoidable. As such, these components may be a source of electric shock hazard. To date, no common guidelines have been prescribed regarding safety when working on electric and hybrid vehicles. In the Republic of Croatia, the Ministry of Labour and Pension System adopted the Regulation on Safety and Health at Work with Electrical Energy in 2012. Although it was written generally for this purpose, point 2 of Article 4 makes its application mandatory in electric and hybrid vehicle service workshops until a special regulation is adopted. In practice, it can be said that worker safety in specialized service workshops depends on the quality of the risk assessment for the workplace, on the employer who must provide protective equipment, and finally on the workers who must comply with the protective measures. However, the question arises as to whether safety and protection engineers and professional associates within authorized companies for preparing risk assessments recognize all the hazards involved in the work of service technicians. This research therefore aimed to show the extent to which safety and protection engineers today are familiar with new technologies in hybrid and electric vehicles and with the hazards posed by the high-voltage components in them. The research results show that they are largely aware of the hazards, but that there is still room for improvement in prescribing a greater amount of protective equipment.

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Original scientific paper

FINITE ELEMENT ANALYSIS OF MUCOSA-SUPPORTED DENTAL GUIDES FOR SAFER IMPLANT SURGERY

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Abstract: *This paper presents a finite element analysis (FEM) of mucosa-supported dental surgical guides used in implantology. In edentulous patients, such guides rely on oral mucosa, a deformable tissue that may influence implant placement accuracy. A simplified three-dimensional model consisting of a dental guide, mucosa, and compact bone was developed in CatiaV5. The model was analyzed under vertical loads from 5 N to 30 N, simulating manual force during implant drilling. Mucosa was modelled as an isotropic linear elastic material. The results show an almost linear relationship between applied force and displacement, confirming that mucosa acts as a compliant interface. Although stresses remain below tissue limits, even small displacements may affect guide accuracy. From a safety perspective, controlled force application is essential to ensure stable guide positioning and accurate implant placement. These findings highlight the importance of considering soft tissue mechanics in the design of surgical guides. Furthermore, the results contribute to a better understanding of biomechanical behavior relevant for improving clinical safety and treatment outcomes.*

Keywords: *dental surgical guides, finite element analysis (FEA), implantology, oral mucosa, biomechanics*

1. INTRODUCTION

Dental surgical guides are widely used in modern implantology as they improve accuracy and reduce the risk of surgical errors [1]. By controlling the position and angulation of drilling instruments, they also reduce the risk of damaging anatomical structures and enhance the predictability of implant placement [2]. In edentulous patients, surgical guides are often supported by oral mucosa [3]. However, mucosa is a deformable biological tissue whose mechanical behavior may significantly influence implant placement accuracy [4].

From the perspective of occupational and patient safety, understanding these biomechanical interactions is essential. Excessive force applied by the surgeon may lead to guide displacement, reduced surgical accuracy, or tissue injury [5]. The finite element method (FEM) enables the simulation of such biomechanical behavior and provides valuable insight into stress distribution and deformation within biological tissues [6]. However, the overall safety of these devices also depends on the accuracy of the digital workflow and the manufacturing process.

Therefore, the aim of this study is to evaluate the biomechanical behavior of mucosa-supported dental guides under clinically relevant loading conditions using finite element analysis, with a focus on their stability and potential impact on implant placement accuracy.

2. MATERIALS AND METHODS

2.1. FEA Model

For the purposes of the research, a simplified three-dimensional geometric model was created using CatiaV5, consisting of three basic components a dental guide, a layer of oral mucosa, and a layer of compact bone of the mandible (Figure 1). The dental guide was modeled as a square plate measuring 20 × 20 mm with a central cylindrical hole representing the drill guide. The thickness of the guide was 3 mm, while the height of the cylindrical drill guide was 6 mm. The oral mucosa layer was modeled as a plate of the same dimensions as the guide, but with a thickness of 1 mm. A 2 mm thick layer of compact bone was modeled below the mucosa, representing the upper part of the mandibular bone.

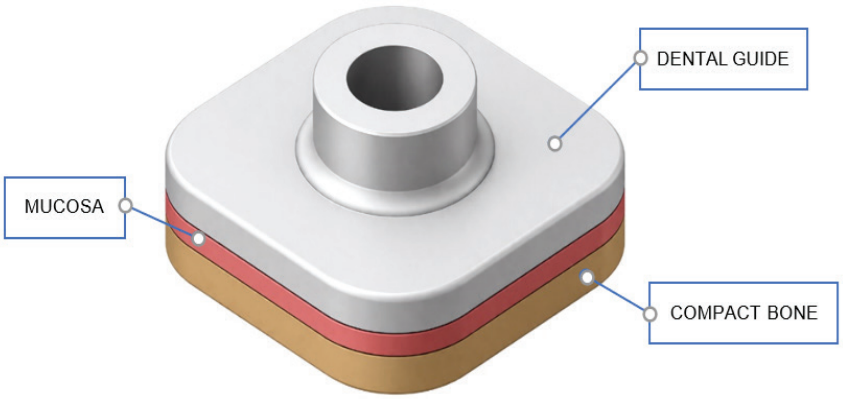


Figure 1: Schematic representation of the analyzed model showing the dental guide, mucosa, and compact bone layers.

The material properties of individual components were defined based on data from scientific literature (Table 1). Linear tetrahedral elements were used for mesh generation [7].

Table 1: Material properties [8–10].

FEA Material	Young's modulus, *E* [MPa]	Poisson ratio, *v*	Density, ρ [kg/m^3]
Compact bone	14000	0,30	1180
Mucosa	37,36	0,47	1050
Dental guide (MED 610)	2200	0,30	1170

The element size in the bone layer was 1 mm, while in the mucosa and dental guide layers it was 0.5 mm (Figure 2).

The boundary conditions of the simulation were defined so that the compact bone layer was completely fixed to simulate its connection with the rest of the mandible. A vertical force was applied to the upper surface of the dental guide in the Z-axis direction, simulating the surgeon's manual pressure. The bone was fixed, while the surgical guide was loaded with a force ranging from 5 N to 30 N to simulate manual force applied by a surgeon during implant drilling. The mucosal displacements and the distribution of Von Mises stresses within the tissue were analyzed [11].

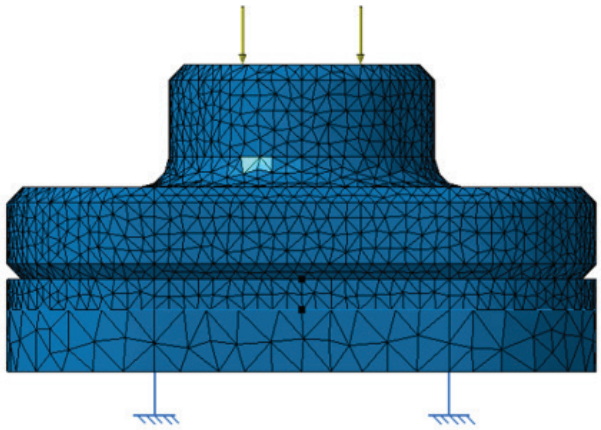


Figure 2: Finite element mesh of the analyzed model with applied load (yellow arrows) and fixed boundary conditions (blue supports).

To accurately simulate a dental guide, it is necessary to select an appropriate material and define its mechanical properties. In this study, MED610 material was selected due to its widespread use in dental applications and the availability of reliable material data [12]. In addition, MED610 exhibits mechanical properties suitable for maintaining sufficient stiffness and dimensional stability during surgical procedures, which is essential for accurate guide positioning.

Materials used for the fabrication of dental guides must meet strict biocompatibility and sterilization requirements. MED610 enables sterilization using ethylene oxide, steam, or gamma radiation, and is suitable for short-term contact with mucous membranes and soft tissues [12]. Proper sterilization reduces the risk of infection and ensures safe intraoral application.

3. RESULTS

The FEA results demonstrate a clear and almost linear relationship between the applied force and the displacement of the mucosa-supported dental guide. As expected, higher loads resulted in increased deformation of the mucosal layer due to its relatively low stiffness compared to the surrounding structures (Figure 4). This behaviour is consistent with previous biomechanical studies that report increased deformation of soft oral tissues under applied load [4,8].

The displacement was predominantly observed in the direction of the applied force (Z-axis), while no displacement occurred in the compact bone due to fixed boundary conditions. This confirms that the mucosa acts as the primary deformable interface within the system (Figure 3 and Figure 4).

The maximum Von Mises stress values ranged from 0.009 MPa to 0.050 MPa, which is significantly lower than the reported tensile strength of oral soft tissues (1.54–3.81 MPa) [4,8]. This indicates that, within the investigated loading range, the applied forces do not pose a risk of mechanical damage to the mucosa. This observation is consistent with clinical and numerical studies indicating that even small guide displacements may contribute to deviations in implant positioning [1,2,10].

However, even relatively small displacements may influence the positional accuracy of the surgical guide and consequently affect implant placement precision.

The mucosa was modelled as a homogeneous, isotropic, and linearly elastic material. However, real oral mucosa exhibits viscoelastic and nonlinear behavior, and therefore the results should be interpreted primarily in a comparative and qualitative manner.

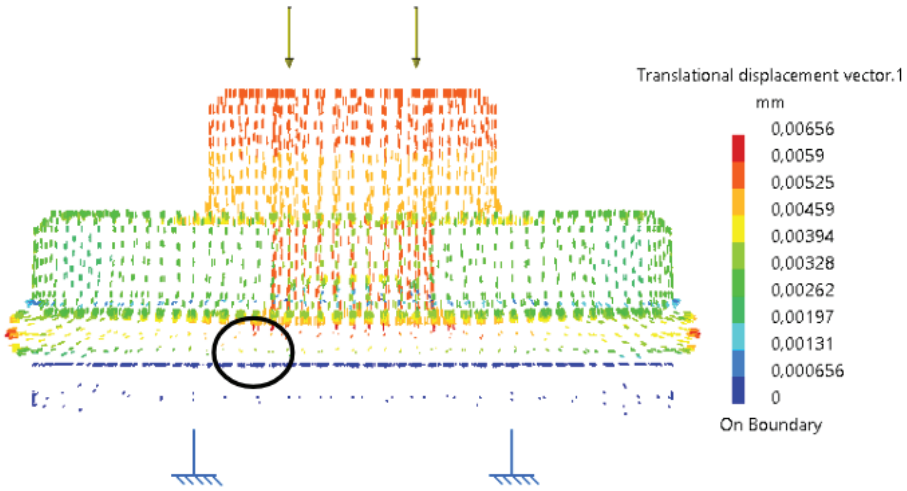


Figure 3: Displacements and selected maximum displacement of the mucosa in the CatiaV5 FEA module.

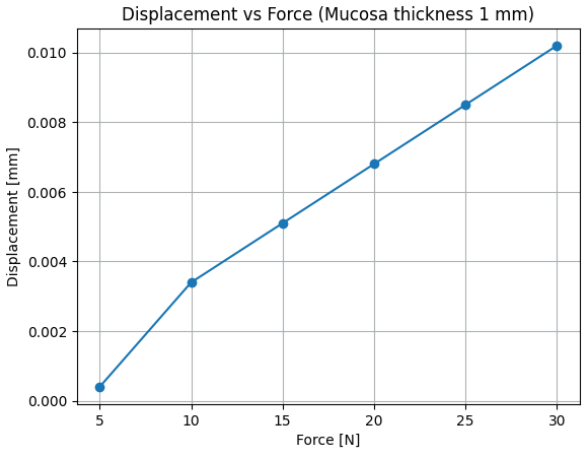


Figure 4: Displacement vs Force.

4. OCCUPATIONAL AND SURGICAL SAFETY CONSIDERATIONS

Occupational and surgical safety represent key aspects in the use of dental guides in implant surgery. Ensuring safe working conditions refers not only to the protection of the patient but also to the protection of medical staff and the optimization of the surgical procedure [5,13].

The use of mucosa-supported dental guides significantly contributes to patient safety. Precise guidance of surgical instruments reduces the risk of:

- damage to vital anatomical structures (e.g., the mandibular canal and nerves),
- incorrect implant positioning,
- excessive trauma to soft and hard tissues [5,14].

Therefore, controlling the applied force during implant surgery is of critical importance [5]. Excessive force may cause instability of the surgical guide and reduced positioning accuracy.

The results suggest that forces up to 30 N remain within safe biomechanical limits for mucosal tissue. This is consistent with existing literature on oral soft tissue tolerance [9], confirming that typical manual forces applied by the surgeon do not cause tissue damage. This further increases the predictability of the procedure and reduces the likelihood of postoperative complications.

However, surgeons should maintain controlled and gradual force application in order to minimize guide displacement and ensure optimal surgical accuracy.

5. CONCLUSION

This study demonstrates that mucosa-supported dental guides exhibit measurable displacement under clinically relevant loading conditions. Although the induced stresses remain well below the mechanical limits of oral soft tissues, the observed displacements may still influence the accuracy of implant placement.

The results confirm that mucosa acts as a compliant biomechanical interface, making the stability of the surgical guide dependent on both applied force and guide design.

Finite element analysis proves to be a valuable tool for evaluating the biomechanical behavior of dental guides and contributes to improving their safety and performance in clinical practice.

These findings highlight the importance of considering soft tissue mechanics in the design of mucosa-supported surgical guides.

Future research should include more advanced material models and patient-specific geometries in order to further improve the predictive capability of such simulations.

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Review article

CFD APPLICATIONS IN OCCUPATIONAL SAFETY: AIRFLOW, VENTILATION AND FIRE ANALYSIS – A REVIEW

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Computational Fluid Dynamics (CFD) has become an important tool in the field of occupational safety and health, enabling detailed analysis of airflow and thermal conditions in working environments. This paper presents a review of CFD applications related to air quality and ventilation in occupational settings. Particular emphasis is placed on the analysis of airflow patterns, identification of poorly ventilated zones and their impact on worker comfort and overall working conditions. In addition, the application of CFD in fire and smoke analysis is also addressed. The paper highlights the advantages and limitations of CFD methods and outlines their potential for improving workplace safety and supporting engineering processes.

Keywords: *Computational Fluid Dynamics (CFD), Occupational Safety and Health, Airflow, Ventilation, Fire and Smoke Analysis*

1. INTRODUCTION

Occupational safety and health increasingly relies on engineering tools that can support the assessment of working conditions before workplaces, ventilation systems or safety measures are implemented. In indoor and industrial environments, airflow distribution, ventilation efficiency and thermal conditions can significantly influence worker comfort, exposure and the overall quality of the working environment.

Computational Fluid Dynamics (CFD) serves as a useful numerical approach for analysing airflow and heat transfer in working environments. Recent studies and review papers have shown that CFD is widely applied for the assessment of ventilation performance, indoor air quality and thermal comfort in different types of buildings and occupational settings [1]–[4]focusing on natural ventilation. The challenges posed by CFD, such as mesh generation, boundary conditions specification, choice of turbulence or radiation models and the ability to estimate the accuracy of results are explored.

For the first time, this work provides a summary of verification and validation studies relating to CFD models of different built environments, and detailed validation studies of naturally ventilated spaces. This review summarises the most common guidelines and conclusions drawn from literature relating to CFD modelling of indoor environments that are naturally ventilated. The work demonstrates current practices in CFD simulation of naturally ventilated indoor environments, highlighting the importance of quality assured validation data to support the credibility of models. The review shows that, despite the presence of best practice guidelines for verification and validation of computational models, the grid verification was infrequently reported in the literature when presenting CFD results of indoor environmental conditions. Moreover, a third of reviewed validation studies were only qualitative and lacked specific validation criteria. Credible CFD analysis of natural ventilation strategies in buildings requires the ability to interpret strongly variable field measurements when specifying boundary conditions, other computational parameters and validating model results. This research provides a background and general guidelines for researchers who are commencing work in the field of CFD simulation of indoor environments for flow problems relating to natural ventilation. A narrative review to credible computational fluid dynamics models of naturally ventilated built environments. One of the main advantages of CFD is the possibility to visualise spatial variations of air velocity, temperature and ventilation effectiveness, which are difficult to evaluate using point measurements alone.

CFD has been applied in various indoor environments, including offices, laboratories, classrooms and other mechanically or naturally ventilated spaces [5]–[8]there has been a significant surge in the adoption of natural ventilation for building indoor spaces, garnering widespread attention. However, the research on human comfort optimization strategies closely related to the effect of natural ventilation is still relatively blank. Therefore, we have taken university laboratories as the research object and studied the use of CFD technology to construct numerical models. Based on previous research on the relevant theories of building ventilation and the impact of various air indicators on human comfort, we simulate the indoor airflow organization of buildings, and propose reasonable optimization design strategies based on simulation results and analysis conclusions. Compared to other studies on NV, we propose a completely new indicator, the Average rate of change in air age (ARCA. These studies demonstrate that numerical simulations can support the evaluation of airflow patterns, temperature stratification and the influence of different ventilation strategies. In addition to airflow and thermal analyses, CFD is also used in fire safety engineering, where smoke movement, temperature development and the effectiveness of smoke extraction systems are important for evacuation planning and emergency response [9]–[12]fire protection is imperative for building construction. Smoke control reduces smoke concentrations as well as the temperature to enable evacuation of building residents. Moreover, firefighters easily extinguish fire with low smoke concentrations and temperatures. In this study, the Fire Research Station, UK standard, was applied to calculate the flow rate of the smoke exhaust fan for a basement with dimensions of 30 m × 20 m × 4 m using a computational fluid dynamic (CFD.

However, CFD should not be understood as a replacement for measurements or professional judgement. The reliability of numerical simulations depends on appropriate modelling assumptions, boundary conditions, mesh quality, turbulence models and, where possible, validation with experimental data [1], [2]focusing on natural ventilation. The challenges posed by CFD, such as mesh generation, boundary conditions specification, choice of turbulence or radiation models and the ability to estimate the accuracy of results are explored. For the first time, this work provides a summary of verification and validation studies relating to CFD models of different built environments, and detailed validation studies of naturally ventilated spaces. This review summarises the most common guidelines and conclusions drawn from literature relating to CFD modelling of indoor

environments that are naturally ventilated. The work demonstrates current practices in CFD simulation of naturally ventilated indoor environments, highlighting the importance of quality assured validation data to support the credibility of models. The review shows that, despite the presence of best practice guidelines for verification and validation of computational models, the grid verification was infrequently reported in the literature when presenting CFD results of indoor environmental conditions. Moreover, a third of reviewed validation studies were only qualitative and lacked specific validation criteria. Credible CFD analysis of natural ventilation strategies in buildings requires the ability to interpret strongly variable field measurements when specifying boundary conditions, other computational parameters and validating model results. This research provides a background and general guidelines for researchers who are commencing work in the field of CFD simulation of indoor environments for flow problems relating to natural ventilation. Therefore, CFD is most useful when applied as a complementary engineering tool that supports decision-making and helps identify potential safety improvements.

The aim of this paper is to present a review of CFD applications in occupational safety, with emphasis on airflow, ventilation, thermal conditions and fire and smoke analysis.

2. COMPUTATIONAL FLUID DYNAMICS AS A TOOL IN OCCUPATIONAL SAFETY

Computational Fluid Dynamics (CFD) is a numerical method used for the analysis of fluid flow, heat transfer and related transport phenomena. In the context of occupational safety, CFD can be used to evaluate how air moves through working environments, how temperature is distributed within enclosed spaces and how different ventilation strategies influence indoor conditions. Unlike simplified calculation methods, CFD provides spatially resolved information about the flow field, which makes it possible to identify areas with low air movement, temperature stratification or unfavourable ventilation patterns.

The application of CFD in occupational environments is particularly useful during the design, assessment and improvement of workplace for example, CFD can be used to assess the position of supply and exhaust openings, the influence of obstacles and equipment, the development of recirculation zones and the effectiveness of air distribution within the occupied zone [1], [2] focusing on natural ventilation. The challenges posed by CFD, such as mesh generation, boundary conditions specification, choice of turbulence or radiation models and the ability to estimate the accuracy of results are explored. For the first time, this work provides a summary of verification and validation studies relating to CFD models of different built environments, and detailed validation studies of naturally ventilated spaces. This review summarises the most common guidelines and conclusions drawn from literature relating to CFD modelling of indoor environments that are naturally ventilated. The work demonstrates current practices in CFD simulation of naturally ventilated indoor environments, highlighting the importance of quality assured validation data to support the credibility of models. The review shows that, despite the presence of best practice guidelines for verification and validation of computational models, the grid verification was infrequently reported in the literature when presenting CFD results of indoor environmental conditions. Moreover, a third of reviewed validation studies were only qualitative and lacked specific validation criteria. Credible CFD analysis of natural ventilation strategies in buildings requires the ability to interpret strongly variable field measurements when specifying boundary conditions, other computational parameters and validating model results. This research provides a background and general guidelines for

researchers who are commencing work in the field of CFD simulation of indoor environments for flow problems relating to natural ventilation.

In addition to airflow analysis, CFD can support the evaluation of thermal conditions. Temperature distribution, heat sources, buoyancy effects and air movement can influence worker comfort and the general quality of the working environment. Recent studies on indoor environments and personalized ventilation also show that CFD can be used to analyze local conditions around occupants, which is relevant when evaluating workplace comfort and ventilation effectiveness [3]the quality of CFD simulations must be maintained through an adequately controlled numerical modeling process. CFD numerical data can explain PV performance in terms of inhaled air quality, occupants' thermal comfort, and building energy savings. Therefore, this paper presents state-of-the-art CFD analyses of PV systems in indoor built environments. The results emphasize the importance of accurate thermal boundary conditions for computational thermal manikins (CTMs.

However, the practical use of CFD requires careful modelling. The reliability of the results depends on the definition of geometry, boundary conditions, mesh quality, turbulence model selection and convergence criteria [1]–[3]the quality of CFD simulations must be maintained through an adequately controlled numerical modeling process. CFD numerical data can explain PV performance in terms of inhaled air quality, occupants' thermal comfort, and building energy savings. Therefore, this paper presents state-of-the-art CFD analyses of PV systems in indoor built environments. The results emphasize the importance of accurate thermal boundary conditions for computational thermal manikins (CTMs. When possible, numerical models should be compared with experimental or field data in order to increase confidence in the simulation results. This is especially important in occupational safety applications, where simulation outcomes may influence decisions related to workplace design, ventilation improvements and preventive safety measures.

Therefore, CFD represents a complementary engineering tool in occupational safety and health. Its main value is not only in calculating airflow or temperature fields, but also in supporting the identification of potentially problematic zones, comparing safety measures and improving decision-making in workplace design and risk reduction.

3. CFD APPLICATIONS IN OCCUPATIONAL ENVIRONMENTS

The application of CFD in occupational environments is broad, since many workplace conditions are directly influenced by airflow, temperature distribution and ventilation performance. In practice, CFD can be used during the planning of new spaces, the improvement of existing ventilation systems or the evaluation of specific safety-related scenarios. Its main advantage is the possibility to analyse the entire spatial field instead of relying only on a limited number of measurement points. The main application areas of CFD in occupational safety considered in this paper are summarized in Table 1.

Table 1: Overview of CFD applications in occupational safety

CFD application	Analyzed parameters	Occupational safety relevance
Airflow and ventilation	Air velocity, flow direction, recirculation zones	Identification of poorly ventilated zones
Air quality and working conditions	Air exchange, air age, ventilation effectiveness	Improvement of indoor working conditions
Thermal conditions	Temperature distribution, stratification, draught risk	Worker comfort and thermal suitability
Fire and smoke analysis	Smoke movement, temperature, smoke extraction	Evacuation support and emergency planning

Based on this overview, the following sections discuss the selected CFD application areas in more detail.

3.1. Airflow and Ventilation Analysis

Airflow and ventilation analysis represents one of the most important applications of CFD in occupational safety. In enclosed working environments, the distribution of supplied and exhausted air is often strongly affected by the position of ventilation openings, internal obstacles, heat sources, equipment layout and the geometry of the space. As a result, ventilation performance can vary significantly within the same room or workplace. CFD makes it possible to analyse these variations by calculating air velocity fields, pressure distribution, recirculation zones and the movement of air through the occupied zone.

This is particularly useful in spaces such as laboratories, offices, classrooms, workshops and industrial halls, where the efficiency of ventilation is important for maintaining acceptable working conditions. Numerical studies of naturally ventilated laboratories have shown that CFD can be applied to evaluate indoor airflow organisation and support optimisation of ventilation strategies [5]. Similarly, CFD studies of office environments indicate that the position of air supply openings and the airflow rate can influence both air quality and thermal comfort [6]. These examples show that CFD can help identify whether the supplied air reaches the relevant working area or whether parts of the space remain insufficiently ventilated. An example of CFD-based airflow analysis in an office environment is shown in Figure 1. The figure illustrates how the position of the air supply opening can influence airflow streamlines and the formation of zones with different ventilation effectiveness.

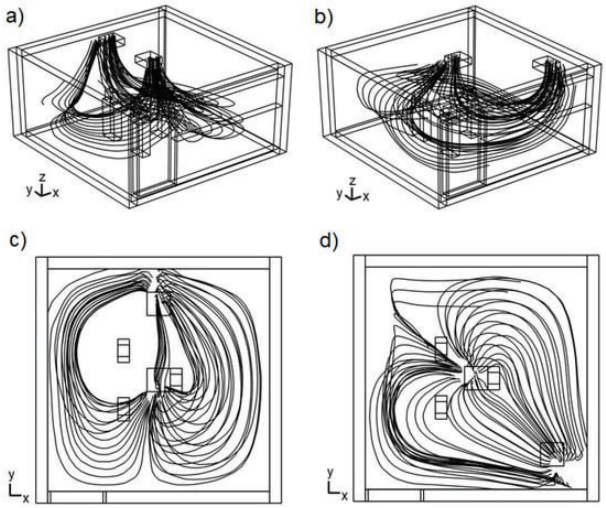


Figure 1: CFD-based airflow streamlines in an office environment [6]

From an occupational safety perspective, the practical value of CFD is in its ability to support preventive design. Before physical modifications are made, different ventilation layouts can be compared numerically. For example, the position of supply and exhaust openings, airflow direction, ventilation rate or the influence of obstacles can be assessed in advance. This can reduce the risk of ineffective ventilation solutions and support more informed engineering decisions.

3.2. Air Quality and Working Conditions

Air quality in occupational environments is closely related to the effectiveness of ventilation and air distribution. Poorly ventilated areas may lead to unfavourable working conditions, especially in spaces where workers spend longer periods of time. CFD can support the assessment of air quality by analysing air movement, air exchange, local air age and the interaction between ventilation and heat sources. In this way, CFD provides a more detailed understanding of how ventilation affects the occupied zone.

Several recent studies have used CFD to assess indoor air parameters in educational and office environments [4], [6], [7]not only to save energy but also due to public health issues such as pandemics. This study focuses on the thermal comfort and air quality of a closed, air-conditioned space located in an extremely hot climate. Due to noise and weather conditions, the door and window of the space are kept closed at all times. The study uses computational fluid dynamics techniques and the finite element method. Average temperatures and CO2 concentrations, as well as effectiveness for temperature and concentration distribution, are calculated for the analysis. Results indicate that supplying air away from hot walls improves air quality and thermal comfort. Furthermore, there is an optimal Reynolds number that depends on the number of people inside the space. Due to the above, it is possible to find an ideal configuration that simultaneously allows for efficient energy use, helps to avoid the adverse effects of CO2 on daily activities such as working or studying, and supports people's health and comfort. Although such environments are not always industrial workplaces, they are relevant from an occupational safety and health perspective because they represent spaces where people work for extended periods.

Another important aspect is the relationship between air quality, thermal comfort and energy efficiency. Modern ventilation systems are expected to provide acceptable indoor conditions while also limiting unnecessary energy consumption. Recent review studies on mechanical ventilation highlight that ventilation design must balance indoor air quality, thermal comfort and energy efficiency [13]. CFD can contribute to this process by enabling comparison of different ventilation strategies before implementation. Therefore, CFD is not only a tool for analysing safety-related parameters, but also a tool for supporting sustainable and efficient workplace design.

3.3. Thermal Conditions in Working Environments

Thermal conditions are an important part of the overall quality of the working environment. In enclosed workplaces, temperature distribution is influenced by ventilation, heat sources, solar gains, equipment, occupancy and the geometry of the space. Even when the average room temperature appears acceptable, local temperature differences and air movement may create less favourable conditions in specific working zones. CFD can be used to analyse these spatial variations and to evaluate how ventilation systems influence the thermal environment.

In occupational environments, thermal conditions are relevant because they affect worker comfort, concentration and the general suitability of the workplace. Numerical studies of indoor environments show that CFD can support the assessment of temperature stratification, air velocity and thermal comfort indicators [6]–[8]. Such analyses are especially useful in spaces where direct measurements at only a few points may not provide a complete picture of the conditions experienced by workers. CFD makes it possible to identify zones with insufficient air movement, excessive temperature gradients or local discomfort caused by draughts.

The practical value of CFD is also related to the comparison of different engineering solutions. Ventilation rates, supply air temperature, diffuser position, exhaust location and internal heat sources

can be analysed before physical changes are implemented. This enables engineers to improve thermal conditions while maintaining efficient system operation. In this way, CFD can support not only occupational safety and health, but also energy-efficient workplace design [13].

3.4. Fire and Smoke Analysis

Although the main focus of this paper is airflow, ventilation and thermal conditions in occupational environments, CFD also has an important role in fire safety engineering. In fire scenarios, the movement of smoke and hot gases is strongly affected by room geometry, ventilation openings, smoke extraction systems and the location of the fire source. CFD can be used to analyse temperature development, smoke movement, airflow patterns and the effectiveness of smoke control systems. Figure 2 illustrates how CFD can be used to visualise fire spread and temperature distribution in a multi-storey building, supporting the assessment of fire development and hazardous thermal conditions.

Recent studies have applied CFD to fire and smoke analysis in basements, car parks, underground garages and multi-storey buildings [9]–[12], [14]fire protection is imperative for building construction. Smoke control reduces smoke concentrations as well as the temperature to enable evacuation of building residents. Moreover, firefighters easily extinguish fire with low smoke concentrations and temperatures. In this study, the Fire Research Station, UK standard, was applied to calculate the flow rate of the smoke exhaust fan for a basement with dimensions of 30 m × 20 m × 4 m using a computational fluid dynamic (CFD. These studies show that numerical simulations can provide useful information for evaluating smoke extraction, ventilation strategies and conditions relevant to evacuation. In enclosed or underground spaces, where smoke accumulation may develop rapidly, CFD can help identify areas where temperature or smoke concentration may become critical for occupants and emergency response.

For occupational safety, fire and smoke analysis is relevant because many workplaces are located in buildings with complex ventilation layouts, underground areas, technical rooms or industrial spaces. CFD can support the assessment of fire-related safety measures by comparing different smoke extraction strategies, ventilation modes and opening configurations. However, fire simulations require careful definition of fire scenarios, heat release rates, boundary conditions and model assumptions. Therefore, CFD in fire safety should be applied with caution and, where possible, supported by standards, experimental data or established fire safety engineering practice.

In this paper, fire and smoke analysis is considered as an additional application area of CFD in occupational safety. It demonstrates that the same numerical approach used for airflow and ventilation assessment can also support the evaluation of emergency scenarios and safety-related engineering decisions. An example of CFD-based temperature distribution during fire smoke development in an enclosed space is shown in Figure 2.

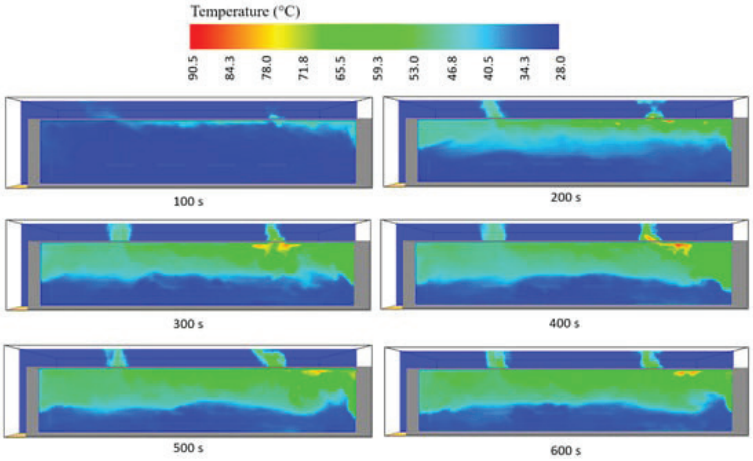


Figure 2: CFD-based temperature distribution during fire smoke development in an enclosed space [15]

4. ADVANTAGES AND LIMITATIONS OF CFD IN OCCUPATIONAL SAFETY

The main advantage of CFD in occupational safety is the possibility to obtain detailed spatial information about airflow, temperature distribution and ventilation performance. While measurements usually provide data only at selected points, CFD enables the analysis of complete flow fields within the investigated space. This makes it possible to identify zones with low air movement, temperature stratification, recirculation or unfavourable ventilation conditions. Such information can support engineers and safety professionals in understanding how workplace layout, ventilation openings, equipment and heat sources influence the working environment.

Another important advantage is the possibility to compare different engineering solutions before they are implemented. CFD can be used to evaluate alternative ventilation strategies, supply and exhaust positions, airflow rates or design modifications. This can reduce the need for costly trial-and-error approaches and may help identify more effective safety measures at an early design stage [1], [2]. In existing workplaces, CFD can also be used as a diagnostic tool to better understand observed problems and to support decisions regarding improvements of ventilation or thermal conditions.

CFD is also useful because it can support the assessment of scenarios that are difficult, expensive or unsafe to investigate experimentally. This is particularly relevant in fire and smoke analysis, where full-scale testing is often limited by cost, safety and practical constraints. Numerical simulations can provide insight into smoke movement, temperature development and the effectiveness of smoke extraction systems [9]–[12], [14]. In this way, CFD can contribute to both preventive occupational safety measures and emergency planning.

Despite these advantages, CFD also has important limitations. The accuracy of simulation results strongly depends on the quality of the input data and modelling assumptions. Geometry simplification, boundary conditions, mesh resolution, turbulence model selection and convergence criteria can significantly affect the results [1]–[3]. If these aspects are not properly defined, CFD simulations may provide misleading conclusions. Therefore, the interpretation of CFD results requires engineering knowledge and a critical understanding of the model limitations.

Validation is another key issue. Whenever possible, CFD results should be compared with experimental or field measurements in order to increase confidence in the numerical model. However, in many practical occupational safety applications, detailed measurement data may not be available. In such cases, CFD should be used carefully and primarily as a comparative tool for analysing trends, identifying potentially problematic zones and supporting decision-making.

Therefore, CFD should not be considered a replacement for measurements, standards or professional judgement. Its strongest value lies in its complementary role. When used appropriately, CFD can improve the understanding of workplace conditions, support the evaluation of safety measures and contribute to better engineering decisions in occupational safety and health.

5. CONCLUSION

Computational Fluid Dynamics represents a valuable engineering tool for supporting occupational safety and health. Its main contribution is the possibility to analyse airflow, ventilation effectiveness and thermal conditions in working environments with a high level of spatial detail. This enables the identification of poorly ventilated zones, unfavourable airflow patterns and areas where thermal conditions may affect the quality of the workplace.

The reviewed applications show that CFD can be used in different occupational environments, including offices, laboratories, classrooms, industrial spaces and enclosed technical areas. In addition to ventilation and thermal analysis, CFD also has an important role in fire and smoke analysis, where it can support the evaluation of smoke movement, temperature development and the effectiveness of smoke control strategies. These applications demonstrate that CFD can contribute to both preventive safety measures and the assessment of emergency scenarios.

However, the reliability of CFD depends on appropriate modelling assumptions, boundary conditions, mesh quality, turbulence model selection and, where possible, validation with experimental or field data. Therefore, CFD should be used as a complementary tool rather than a replacement for measurements, standards or professional judgement.

Overall, CFD has significant potential for improving workplace safety and supporting engineering decision-making processes. When applied properly, it can help engineers and safety professionals better understand working conditions, compare possible safety measures and support the development of safer and more efficient occupational environments.

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Original scientific paper

BIO-INNOVATIVE PRETREATMENT APPROACH FOR COTTON KNIT FABRIC

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Abstract: *In this paper, a bio-innovative pretreatment approach for cotton knit fabric and its effects on fabric comfort and appearance were studied. Raw cotton interlock knit fabric was desized with α-amylase and bioscoured using neutral pectinase, then compared with alkaline scouring using Na_2CO_3, a milder alternative to NaOH. Subsequent chemical bleaching was performed with sodium percarbonate, providing a less aggressive process at lower pH than conventional peroxide bleaching. Fabric comfort and whiteness were evaluated. Both bioscouring and alkaline scouring achieved good whiteness, but enzymatic treatment resulted in considerably improved tactile properties, enhanced softness and hand feel, and effective moisture absorption and transport after bleaching, highlighting better comfort in enzyme pre-treated fabrics. Therefore, it can be a viable and more sustainable alternative to conventional alkaline scouring, allowing optimization of sensory and thermo-physiological comfort in cotton interlock knitted fabrics.*

Keywords: *cotton interlock knit fabric, amylase, pectinase, percarbonate bleach, MMT, FTT*

1. INTRODUCTION

Raw cotton knit fabric contains starch size added before knitting, and non-cellulosic impurities that grew on the fiber, such as pectins, waxes, proteins, and minerals, mainly located in the fiber primary cell wall. These impurities limit the inherent hydrophilicity of cotton, negatively affecting finishing processes, moisture transport, and overall wearing comfort, so it is necessary to remove them in pretreatment processes such as desizing, scouring, and chemical bleaching [1-5]. Conventional scouring, performed under strongly alkaline conditions using sodium hydroxide or sodium carbonate at high temperature, effectively removes non-cellulosic impurities, but also consumes energy and water, and causes fiber weight loss reducing the softness. Enzymatic treatments are environmentally friendly alternatives to alkaline scouring due to their mild operating conditions and substrate specificity. Amylases, pectinases, lipases, and cellulases are used in cotton processing [1-5]. Neutral pectinase in bioscouring improves cotton hydrophilicity, whiteness, and sewability, while reducing fiber damage and enhancing process sustainability [1,4,5]. However, enzyme treatments do not remove all hydrophobic impurities completely, so they affect moisture transport and color. Therefore, chemical bleaching is often applied to improve fabric wettability and whiteness [3,5]. Hydrogen peroxide is usually used as bleaching agent, but it must be activated at pH value higher

than 9.5 to increase the rate of decomposition. NaOH activation can be highly damaging to fibers if the alkalinity increase above pH 10. In contrast, sodium percarbonate conveniently provides its own alkalinity through the sodium carbonate component upon dissolution, immediately raising the pH to the optimal range. Its decomposition begins around pH 7 and is optimal at pH 8.5, so it is milder on most textiles [6].

Fabric comfort is a critical factor in clothing performance and strongly influences wearer satisfaction and product acceptance. Psychological comfort relates to visual appearance and aesthetic perception, while sensory comfort refers to tactile sensations such as softness, smoothness, and friction. Thermo-physiological comfort is associated with heat and moisture transfer between the body and the environment through the clothing system. In cotton fabrics, both comfort dimensions are strongly affected by chemical and enzymatic pretreatments, which modify surface morphology, hydrophilicity, and internal pore structure. Therefore, a combined evaluation of tactile and moisture management properties is necessary to fully characterize fabric comfort performance [7,8]. In this study, the influence of neutral pectinase scouring versus alkaline scouring on the comfort-related properties of interlock knitted cotton fabrics was researched.

2. MATERIAL AND METHODS

The fabric used was a circular weft interlock knitted fabric of 100% raw cotton yarn (20 tex), mass per unit area 220 g/m^2, produced in the company Pamučna industrija Duga Resa. Fabric was desized using α-amylase, then alkali or bio-scoured, and chemically bleached with percarbonate. All pretreatments were performed by the exhaust method with a liquor ratio of 1:10 in the drum of in a Polycolor Turbomat P4502 (Mathis) dyeing machine using 1% Felosan RG-N (non-ionic surfactant, ethoxylate fatty alcohol by CHT-Bezema) as wetting agent. Fabric desizing was performed using 3% owf α-amylase (Beisol T2090, CHT-Bezema), and bio-scouring was performed using 3% owf pectinase complex (Biosol PRO, CHT-Bezema). The enzyme processes were carried out at 60 °C for 40 min, at pH 7. Alkaline scouring was performed using 10 g/l Na_2CO_3 at 95 °C, for 60 min, at pH 9, followed with rinsing and neutralization in 5% CH_3COOH. Percarbonate bleaching was performed at 60°C for 60 min, pH 8, in bath containing 15 g/l $Na_2CO_3x1.5H_2O_2$, 2 g/l Contavan ALR (stabilizing agent by CHT-Bezema). Labels and pretreatments are listed in Table 1.

Spectral remission was measured on a remission spectrophotometer Spectraflash SF 300 (Datacolor) using “Measuring until tolerance” command which means that at least 10 measurements at must be made. The whiteness degree according CIE (W_{CIE}) was calculated automatically in accordance to ISO 105-J02:1997. Moisture management properties were determined according to AATCC TM 195-2017 using the Moisture Management Tester (MMT) M290 (SDL Atlas) on 5 parallel samples. Fabric hand (touch) properties were determined according to AATCC TM 218-2025 using the Fabric Touch Tester (FTT) M293 (SDL Atlas) on 4 parallel samples. Before measuring on MMT and FTT, samples were conditioned for 24 hours in the air conditioning chamber KBF-S 240 E6, 9020-0366 (Binder GmbH) to standard conditions, RH 65±4 % and temperature 20±2 °C.

3. RESULTS AND DISCUSSION

This paper researched a bio-innovative pretreatment approach for cotton knit fabric. An interlock cotton knit fabric was desized with α-amylase, scoured with pectinase, and percarbonate bleached. The comfort-related properties were determined and compared to those of alkaline scoured fabrics followed by percarbonate bleaching. Before determining comfort-related properties, spectral properties of the cotton knit fabrics were measured, and the whiteness degree according to CIE (W_{CIE}) was calculated from spectral remission values. The whiteness degree (W_{CIE}) presented in Table 1 clearly show improvement in fabric whiteness with each pretreatment.

Table 1: Labels, pretreatments and whiteness degree according to CIE (W_{CIE}) of cotton knit fabrics

Label	Fabric state/ Pretreatment	W_{CIE}
R	Raw, sized	-18.5
D	Desized using α-amylase	0.2
AS	Desized, then alkali scoured	24.9
BPS	Desized, then bio-scoured with pectinase	10.9
AS _PCB	Percarbonate bleached, alkaline scoured	51.3
BPS_PCB	Percarbonate bleached, bio-scoured	52.3

The raw fabric exhibited a negative whiteness value, reflecting the presence of natural pigments, waxes, pectins, seed fragments, and sizing agent, that give untreated cotton yellowish color. After enzymatic desizing, the whiteness slightly increased because it primarily removes applied sizing agents rather than naturally occurring color. A substantial increase in whiteness was observed after alkaline scouring due to the removal of non-cellulosic impurities. The bioscoured fabric achieved better whiteness than that of the desized fabric, but lower than AS sample. This indicates that pectinase treatment removed some non-cellulosic impurities but in lower extent than in alkaline scouring. Residual waxes and colored compounds likely remained on the fiber surface, limiting the increase in whiteness. The highest whiteness values were obtained after percarbonate bleaching. Both samples reached whiteness >50, proving effectiveness of sodium percarbonate as an oxidizing bleaching agent. Interestingly, the BPS_PCB sample exhibited higher whiteness value than AS_ PCB sample. Although the difference is small, it suggests that bioscouring followed by percarbonate bleaching can achieve whiteness levels comparable to, or even slightly better than, those obtained through conventional alkali scouring and percarbonate bleaching.

To objectively evaluate comfort-related properties, the Moisture Management Tester (MMT) and the Fabric Touch Tester (FTT) was used. Results are shown in Table 2 and Table 3. The raw fabric (R) and desized fabric (D) exhibited poor moisture management, having no bottom wetting times in 120 s and zero bottom absorption rate, maximum wetted radius, and spreading speed. The negative R values indicate that moisture remained on the top surface without any transport, and fabrics are classified as waterproof fabrics. Although enzymatic desizing successfully removes starch-based size materials, the results suggest that α-amylase was insufficient to eliminate the hydrophobic non-cellulosic impurities naturally present in cotton. Alkaline scoured fabric (AS) showed significant improvement in moisture management; wetting times decreased to <4 s, spreading speed and wetted radius increased. The one-way transport index became highly positive (163.97%), indicating effective transfer of moisture from the skin-contact side to the outer surface, and the fabric was classified as a moisture management fabric. The removal of hydrophobic impurities during alkali scouring increased fiber hydrophilicity and facilitated water penetration and transport through the fabric structure. The bioscoured fabric (BPS) exhibited only limited improvement compared with

the raw and desized fabrics. Although the bottom wetting time decreased, the values remained considerably lower than those obtained for AS fabric. The negative R value and very low OMMC indicate poor moisture transport capability, and fabric is classified as water repellent.

Table 2: The Liquid Moisture Management Properties of alkali and bio-scoured cotton knit fabrics

Sample		**R**		**D**		**AS**	
Property		Mean	CV	Mean	CV	Mean	CV
WT (s)	T	10.57	0.05	11.22	0.03	3.81	0.08
	B	120.00	0.00	120.00	0.00	3.69	0.03
AR (%/s)	T	377.83	0.08	438.35	0.05	33.37	0.02
	B	0.00	0.00	0.00	0.00	42.89	0.03
MWR (mm)	T	5.00	0.00	5.00	0.00	15.00	0.00
	B	0.00	0.00	0.00	0.00	20.00	0.00
SS (mm/s)	T	0.47	0.05	0.44	0.03	2.73	0.04
	B	0.00	0.00	0.00	0.00	3.23	0.04
R (%)		-926.94	0.12	-1004.33	0.05	163.97	0.09
OMMC		0.00	0.00	0.00	0.00	0.52	0.03
Type		*Water proof fabric*		*Water proof fabric*		*Moisture management fabric*	
Sample		**BPS**		**AS_PCB**		**BPS_PCB**	
Property		Mean	CV	Mean	CV	Mean	CV
WT (s)	T	10.14	0.18	4.05	0.02	3.94	0.15
	B	97.09	0.21	3.86	0.07	4.25	0.03
AR (%/s)	T	460.51	0.06	33.85	0.03	32.59	0.07
	B	17.58	1.06	44.44	0.01	46.29	0.01
MWR (mm)	T	5.00	0.00	15.00	0.00	15.00	0.00
	B	3.33	0.87	15.00	0.00	15.00	0.00
SS (mm/s)	T	0.50	0.19	2.55	0.03	2.45	0.02
	B	0.04	0.87	2.66	0.04	2.51	0.01
R (%)		-896.90	0.10	161.68	0.05	217.49	0.03
OMMC		0.03	1.31	0.47	0.02	0.52	0.02
Type		*Water repellent fabric*		*Moisture management fabric*		*Moisture management fabric*	

T (top surface) and B (bottom surface), Wetting Time – WT, Absorption Rate – AR, Maximum Wetted Radius – MWR, Spreading Speed – SS, Accumulative One-way Transport Capability – R, Overall (liquid) Moisture Management Capability – OMMC, and Type of fabric

These findings suggest that the pectinase treatment removed some pectic substances but was insufficient under the applied conditions to achieve the extensive impurity removal. Bleaching with sodium percarbonate significantly enhanced the moisture management of both fabrics – lower wetting times (4 s), high absorption rates, large wetted radii, high spreading speed, increased transport. The higher R value observed for BPS_PCB suggests that pectinase treatment which partially removed pectin and improved fiber accessibility, was complemented by subsequent percarbonate bleaching. Obtained OMMC values for AS_PCB and BPS_PCB, classify them as moisture management fabrics, indicating that bioscouring and percarbonate bleaching can provide similar fabric properties to the ones achieved by alkaline scouring and percarbonate bleaching.

The primary sensory indices shown in Table 3, and its differences, indicate that cotton fabric pretreatment significantly affected and altered fabric surface and its tactile comfort. The relatively high smoothness is due to the starch size which was added to reduce surface irregularities and

friction. In alkali scouring (AS) smoothness is reduced as it removed natural waxes and surface impurities, and increased surface roughness. Smoothness of bioscoured fabrics (BPS) suggest that enzymatic treatment preserved the fabric surface more effectively than harsh alkaline scouring. After percarbonate bleaching, smoothness remains, indicating that enzymatic pretreatment kept surface quality after bleaching. Softness varied considerably among the treatments. The lowest softness values were found in the raw fabric, particularly on the back surface (0.04), indicating a relatively harsh handle. Desizing slightly improved softness, reflecting the beneficial effect of size removal on fabric flexibility. The highest softness values were observed in the bioscoured fabric (BPS). This suggests that pectinase treatment effectively removed non-cellulosic impurities while preserving the integrity of the cellulose fibers, resulting in a softer and more pleasant handle. Alkali-scoured fabric (AS) also showed improved softness on the face surface, though the back surface value was much lower. After bleaching, softness decreased substantially in AS_PCB, indicating that the combined action of alkaline scouring and bleaching increased fiber rigidity. In comparison, BPS_PCB retained higher softness values, further supporting the gentler nature of enzymatic pretreatment. High warmness was observed, but it was expected as it is influenced by fabric bulk, air retention, and thermal conductivity. Bleaching slightly reduced warmness on the back surfaces of both AS_PCB and BPS_PCB, likely due to changes in surface morphology and increased openness of the fiber structure after oxidation. The total sensory index provides an overall assessment of tactile comfort. Among all samples, bioscoured fabric (BPS) had the highest total hand values, indicating the most balanced combination of smoothness, softness, and warmness. These results demonstrate that enzymatic bioscouring can enhance comfort-related properties while minimizing fiber damage. Alkali-scoured fabric (AS) showed a moderate total hand value. After percarbonate bleaching, total hand values decreased for both fabrics due to oxidative effects that increased fiber stiffness and reduced softness. However, the BPS_PCB maintained a higher total hand value than AS_PCB, indicating superior retention of sensory comfort.

Table 3: FTT Primary Sensory Indices of cotton knit fabrics

		Primary Sensory Indices			
Sample		**Smoothness**	**Softness**	**Warmness**	**Total**
R	face	0.11	0.15	0.80	0.29
	back	0.42	0.04	0.51	0.32
D	face	0.21	0.19	0.80	0.31
	back	0.56	0.22	0.86	0.53
AS	face	0.14	0.31	0.92	0.38
	back	0.11	0.11	0.69	0.15
BPS	face	0.21	0.37	0.83	0.41
	back	0.23	0.38	0.84	0.39
AS_PCB	face	0.13	0.05	0.85	0.28
	back	0.26	0.24	0.49	0.15
BPS_PCB	face	0.15	0.16	0.83	0.33
	back	0.34	0.15	0.55	0.23

4. CONCLUSION

This study investigated bio-innovative pretreatment approach for cotton interlock knitted fabric involving enzymatic desizing with α-amylase, bioscouring with pectinase, and bleaching with sodium percarbonate. The comfort-related properties of the treated fabrics were evaluated and compared

with those obtained using conventional alkaline scouring, both before and after percarbonate bleaching. The results showed that the combination of bioscouring and percarbonate bleaching can achieve fabric performance comparable to conventional alkaline pretreatment after bleaching, while offering advantages in softness, fabric handle, and sustainability. These findings demonstrate that pectinase bioscouring, followed by percarbonate bleaching, represents a viable environmentally friendly alternative to conventional alkaline scouring for the pretreatment of cotton interlock knitted fabrics.

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Original scientific paper

APPLICATION OF DEEP LEARNING IN HUMAN AND ENVIRONMENTAL SAFETY

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Abstract: *The rapid development of computer systems and the ubiquity of multimedia content have created a strong demand for the automated analysis and interpretation of visual information. In this context, image segmentation represents one of the most critical and challenging steps in computer vision and digital media processing, as it enables the precise identification, localization, and extraction of key regions of interest within visual content. The aim of this study is to conduct a comparative analysis and evaluation of three distinct methodological approaches to image segmentation: a classical clustering algorithm (K-Means), a fuzzy logic-based algorithm (Fuzzy C-Means), and a contemporary deep neural network architecture (Mask R-CNN). Realistic traffic scenarios frequently encountered by drivers - where the accuracy of object recognition (such as pedestrians, vehicles, and traffic signs) is directly critical to human safety - were selected as the primary evaluation domain. This research not only provides a comprehensive analysis of the effectiveness of these segmentation approaches, but also highlights their respective advantages and limitations in practical safety-critical applications.*

Keywords: *safety, K-Means, Fuzzy C-Means, Mask R-CNN, deep learning*

1. INTRODUCTION

As one of the key techniques in image processing, segmentation enables the extraction of the object of interest from complex scenes, which is crucial for converting visual information into a structural form suitable for future analysis, especially in modern applications such as medical diagnostics, autonomous vehicles, and robotic vision. These systems facilitate a higher-level understanding of visual scenes, thereby enabling accurate object classification, behavior analysis, and decision-making critical to human and environmental safety. The traditional approach to segmentation using the K-Means algorithm is valued for its execution speed and simplicity but is limited to precisely defined boundaries between clusters and the assignment of each data point to exactly one cluster. Alternatively, the Fuzzy C-Means (FCM) algorithm provides a fast and simple implementation that utilizes a membership function ranging from 0 to 1, allowing for improved modeling and softer cluster boundaries. The main drawback of both algorithms is their reliance on a predefined number of clusters, alongside high sensitivity to initial parameter initialization. [1, 4, 11]

The emergence and rapid development of convolutional neural networks (CNN) have significantly changed the segmentation paradigm. An example is Mask R-CNN, which not only performs object detection and classification but also provides precise instance segmentation at the pixel level. This approach demonstrates superior robustness in complex environments where traditional algorithms frequently fail due to noise or object occlusion. [12]

The primary objective of this research is to perform an empirical evaluation and comparative analysis of these algorithms in safety-critical, real-world scenarios. This study aims to delineate the specific advantages and limitations of traditional segmentation methods in comparison to modern deep learning models. The performance comparison was conducted across the entire dataset using five key metrics: execution time, overall accuracy, Intersection over Union (IoU), recall, and the Dice coefficient. [1]

2. ALGORITHMS AND METRICS

This chapter describes the theoretical framework of the work, which includes preparing the dataset, the main features of the three analyzed algorithms, and the definition of the metrics used to assess their performance. For the purpose of experimental evaluation, images from the publicly available and widely recognized COCO *(Common Objects in Context)* dataset were used. From this set, three characteristic images were selected to serve as test samples. The chosen images were intentionally of different geometric dimensions (resolutions), have completely different color palettes and lighting intensities, and contain varying arrangements as well as numbers of objects within the scene. This approach to data selection allows for rigorous testing of the algorithms' robustness in real and unpredictable computer vision conditions, as well as their later comparison.

Before the segmentation phase itself, the images were subjected to a preprocessing process. This step involved normalizing the contrast and scaling the dimensions into a uniform format tailored to the input requirements of the Mask R-CNN model. For validation and evaluation purposes, the original high-precision annotations and binary object masks integrated based on the COCO database itself were used as reference masks (ground truth). [7]

K-Means is a traditional unsupervised machine learning algorithm whose main purpose involves dividing a dataset into a predefined number of clusters *K*, while also minimizing variability within each cluster and maximizing the difference between multiple clusters. Unlike hierarchical approaches, K-Means operates on the principle of "hard" assignment, where each pixel can belong to only one cluster. One of the main applications of the K-Means algorithm is in the field of image and video processing, where it is used for segmentation. In this context, the algorithm groups image pixels according to their characteristics (e.g., color, intensity, texture), enabling the extraction of distinct objects or regions. [3, 6]

The process minimizes the sum of squared distances between the pixels and their corresponding centroids , which is mathematically expressed through the function *J*:

$$J = \sum_{j=1}^{K} \sum_{i=1}^{n} \| x_i^{(j)} - \mu_j \|^2$$

The main drawback of this method in image segmentation is its high sensitivity to the initial choice of centroids and noise, as well as completely ignoring spatial context and shape semantics. [3, 6]

Fuzzy C-Means (FCM) algorithm is an extension that introduces the principles of 'fuzzy' logic, allowing each pixel to belong to multiple clusters at the same time, with the degree of membership expressed using membership functions. This approach is particularly useful in image segmentation problems, where the boundaries between objects are not always clearly defined, making it necessary to model uncertainty and overlap between classes. The membership value is in the range 0 - 1, and the objective function that the algorithm minimizes is defined as:

$$J_m = \sum_{i=1}^{N} \sum_{j=1}^{C} u_{ij}^{m} \|x_i - c_j\|^2$$

where *m* is a parameter that determines the level of fuzziness, while is the cluster centroid. FCM delivers better results on transitional and blurred object boundaries compared to K-Means, but it maintains high complexity. [3, 6]

Mask R-CNN is an advanced deep learning architecture designed for instance segmentation. The model simultaneously performs object classification, bounding box regression, and pixel-level binary mask for each detected instance. The key innovation of this architecture is the *RoIAlign* layer, which eliminates the spatial coordinate quantization present in traditional pooling methods. By enabling precise alignment of high-level extracted features with the original image geometry, *RoIAlign* directly improves the accuracy of predicted mask boundaries. The overall execution pipeline proceeds through three main stages: first, the model scans the input image using a Region Proposal Network (RPN) to identify candidate regions likely containing objects of interest. Next, for each detected region, the network concurrently predicts the object class category and refines the bounding box coordinates. Finally, a dedicated fully convolutional branch extracts pixel-level object contours within each bounding box, generating a precise binary mask that effectively delineates the object from its background. [5, 6]

To objectively evaluate the performance of each algorithm, it is necessary to introduce quantitative metrics that allow for measuring the quality of segmentation against a known solution, ground truth mask. The comparative performance analysis and validation of model efficiency were conducted by tracking five key metrics for each image:

- Execution Time: Represents the total time interval needed for the algorithm to process a single image and generate the final mask, which is crucial for real-time applications. The complexity of the algorithm significantly affects it.
- Accuracy - Acc: Represents the overall percentage of correctly recognized and classified pixels in the image, including both the object and the background. This metric gives a general idea of the algorithm's performance but can be misleading with unbalanced data when the number of background pixels far exceeds the number of object pixels. $Acc = \frac{TP+TN}{TP+TN+FP+FN}$ [2, 3]
- Intersection over Union - IoU: Refers to a standard metric that measures the extent of geometric overlap between the algorithm-predicted mask and the ground truth mask. $IoU = \frac{TP}{TP+FP+FN}$ [2, 3]

- Recall - Rec: Measures the algorithm's ability to correctly identify and cover all true pixels of the target object. A high recall indicates that the majority of the object has been detected, but it does not guarantee that all classified pixels are accurate or free from false positives. $Rec = \frac{TP}{TP+FN}$ [2, 3]
- Dice coefficient: Represents a harmonic measure of similarity that evaluates contour matching and is a key indicator of the quality of the generated mask. $Dice = \frac{2*TP}{2*TP+FP+FN}$ [2, 3]

Mathematical definitions of the applied metrics are based on the pixel-level confusion matrix, where TP (True Positive), TN (True Negative), FP (False Positive), and FN (False Negative). [3]

The overall accuracy metric (Acc), although fundamental, suffers from a well-known limitation referred to as the accuracy paradox in scenarios characterized by significant class imbalance. Given that background pixels in the test images from the COCO dataset typically occupy a considerably larger area than the target objects, an algorithm could attain a high Acc value simply by classifying the majority of pixels as background - even if it completely fails to segment the fine object contours. Consequently, the primary focus of the evaluation is placed on Intersection over Union (IoU) and the Dice coefficient. These two metrics are mathematically more rigorous because they disregard correctly classified background pixels and concentrate exclusively on the overlap between the predicted mask and the ground truth. While IoU penalizes even minor spatial deviations, offering a stringent assessment of geometric alignment, the Dice coefficient acts as a harmonic mean that is closely correlated with recall. A high recall score guarantees that the algorithm successfully captured the full region of the target object, however, only in combination with a high IoU value does it confirm that the predicted mask does not over-extend beyond object boundaries. Furthermore, incorporating execution time as an evaluation parameter establishes the necessary trade-off between computational complexity and geometric accuracy. [3]

3. EXPERIMENTAL PART

This section provides a detailed description of the practical and methodological frameworks of the research, including the experimental setup parameters, the characteristics of the selected test samples, and their preprocessing procedures for algorithm execution. All experiments and performance evaluations were conducted on the same hardware environment (Intel Core i5-8250U CPU, 8 GB DDR4 RAM, Intel UHD Graphics 620 GPU) to ensure consistent and comparable measurement of execution time.

On the software side, the algorithms were implemented in Python using modern computer vision and machine learning libraries:

- *PyTorch / TorchVision*: Used as the main deep learning framework, for loading pretrained Mask R-CNN model weights, and tensor manipulation.
- *OpenCV (Open Source Computer Vision Library)*: Used for loading images, color space transformations (RGB to Lab and grayscale), basic pixel operations during clustering, and converting results back to the RGB color space.
- *NumPy* and *Scikit-Learn*: Used for mathematical operations on matrices, implementing Euclidean distance, and running standard K-Means and FCM algorithms.

Prior to the segmentation process, the input data underwent a standardized preprocessing stage. For the K-Means and Fuzzy C-Means algorithms, images were transformed into an appropriate color space to facilitate distance calculations between pixel feature vectors and cluster centroids. For the Mask R-CNN model, dynamic resizing and color channel normalization were performed to align with the input specifications of the pre-trained architecture. Additionally, target object detection was configured to extract specific COCO dataset classes, including pedestrians, cars, trucks, bicycles, motorcycles, traffic lights, and wildlife (e.g., bears). The inclusion of these classes directly reflects real-world traffic hazard scenarios, forming a core contribution of this work toward enhancing human safety and environmental co-existence through computer vision. [5, 8]

To ensure experimental reproducibility, specific implementation configurations were set for each algorithm. Both K-Means and Fuzzy C-Means were executed on grayscale image representations using a fixed cluster count of $K = 3$, corresponding to the primary scene components: background, road surface, and target objects. FCM was configured with a weighting exponent $m = 2.0$, and maximum iteration limit of 30. For K-Means, convergence criteria were set to a maximum of 10 iterations with an epsilon of 1.0. To resolve the class-ambiguity inherent to unsupervised clustering, cluster-to-ground-truth mapping was automated by selecting the cluster mask yielding the highest IoU overlap. For deep learning inference, the pre-trained Mask R-CNN model with a *ResNet-50-FPN* backbone was deployed on a CUDA-enabled GPU. Predictions were filtered using a confidence score threshold of $S > 0.50$ alongside a mask binarization threshold of 0.50.

As previously stated, three representative images were selected from the COCO dataset to evaluate the performance of the proposed methods. The selection process was deliberately designed to introduce a high degree of heterogeneity across the samples, thereby evaluating the algorithms under realistic and challenging conditions involving traffic safety, human behavior, and environmental interaction with wildlife. The selected test images are presented in Figure 1, with their primary characteristics outlined below.

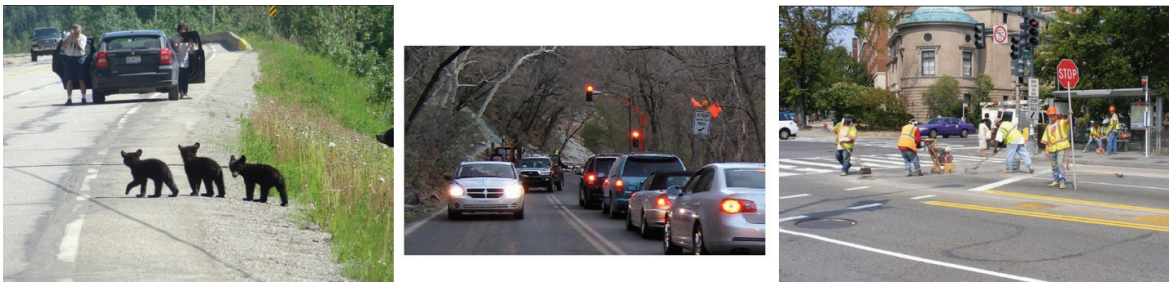


Figure 1: Images for the experimental part

- **The Challenge of Unpredictable Enviromental Events**

  The first test image depicts a critical scenario that combines traffic safety with unpredictable environmental factors (wildlife hazards). In the foreground, three bear cubs are positioned at the immediate edge of a roadway, presenting a severe collision risk and a potential safety hazard due to the likely proximity of an adult female bear. Furthermore, pedestrians standing outside their vehicles near the animals obstruct traffic and compromise overall road safety. From a computer vision perspective, the primary challenge in this scene lies in the low contrast between the dark fur of the animals, vehicle shadows, and the asphalt surface.

- **The challenge of Temporary Signage and Dynamic Lighting**

  The second test image features a queue of vehicles in both lanes operating under temporary traffic signal control in a forested area. In the foreground, a stationary vehicle's headlights generate a high-intensity light beam. This scene evaluates algorithmic robustness against severe lighting anomalies and the accurate detection of non-permanent traffic control infrastructure. Additionally, it presents the challenge of segmenting closely spaced instances belonging to the same object class. Consequently, this sample serves as a direct stress test for K-Means and Fuzzy C-Means regarding their susceptibility to cluster ambiguity and boundary misallocation between objects and the background.

- **The challenge of Scene Complexity and Object Overlap**

  The third test image captures an active daylight construction zone at a dense urban intersection. The scene features multiple construction workers wearing high-visibility fluorescent vests while operating pavement-cutting equipment and performing manual maintenance. The background consists of complex urban architecture, moving traffic, and heterogeneous signaling devices. This image was selected due to its high spatial noise, high object density, and the necessity to accurately isolate vulnerable road users (construction workers) from a cluttered background. Ultimately, this sample evaluates the algorithms' capacity to maintain pixel-level precision along irregular boundaries - a task that poses a significant challenge for traditional segmentation methods lacking high-level semantic context.

For each of the selected images, a binary reference mask of the same dimensions was generated. Pixels that belong to the target safety classes (pedestrians, workers, vehicles, wildlife, traffic lights) are marked with a value of 255 (white), while all other background pixels (road, vegetation, sky, buildings) are set to 0 (black). These masks serve as the absolute reference for calculating segmentation performance metrics.



Figure 2: Reference masks for the experimental part

4. RESULTS

This chapter presents and analyzes the experimental results obtained for each test image. To ensure methodological consistency, the evaluation is divided into two main components:

- *Quantitative (numerical) evaluation*: Focuses on the precise statistical computation of overlap and pixel classification accuracy against ground truth masks. All performance metrics, accuracy (Acc), intersection over union (IoU), recall (Rec), and the Dice coefficient, are normalized on a scale from 0 (complete lack of overlap) to 1 (perfect geometric reconstruction). Additionally, temporal efficiency is reported in seconds, measured to a precision of four decimal places (tenths of a millisecond).

- *Qualitative (visual) evaluation*: Focuses on morphological fidelity and visual inspection, analyzing each algorithm's capability to preserve edge smoothness, isolate fine geometric details, and suppress complex background texture noise.

The first test image features wildlife in the immediate foreground positioned on a gray asphalt surface, with two vehicles and two pedestrians occupying the background. From a computer vision perspective, this scene introduces significant morphological and spectral challenges due to the following factors:

- High-Frequency Background Complexity: The background is highly heterogeneous, with high-frequency details (various shades of gray, shadows, and variations in relief). This kind of texture noise makes it difficult for traditional algorithms to detect continuous edges.
- Spctral Overlap in the color space: The dark shades in the young animals' fur and the dark tones in the background share similar intensity values in the RGB spectrum, which represents a direct obstacle for K-Means and Fuzzy C-Means algorithms, which, due to relying on pure pixel color, tend to mistakenly group parts of the background with object elements.
- Objects in Close Proximity: The cubs are situated in close physical proximity to one another, while the vehicles partially overlap with the pedestrians in the background.

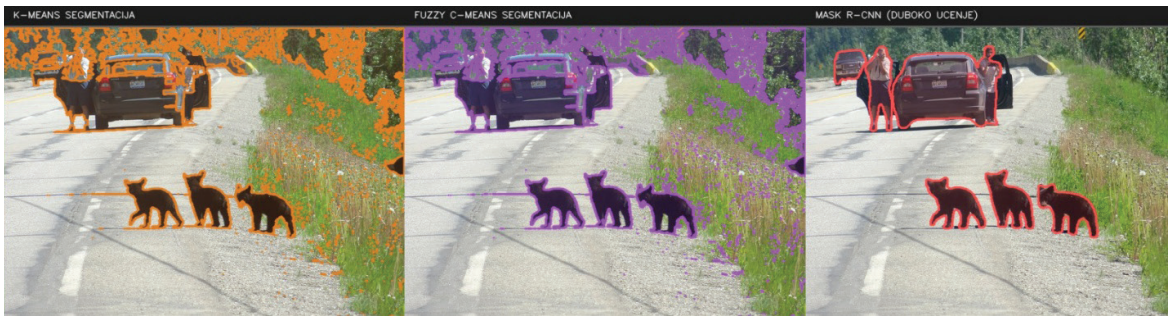


Figure 3: Application of segmentation algorithms to the first image

In Figure 3, a series of errors in the K-Means and FCM algorithms can be observed. The stationary vehicle does not have clearly defined edges, nor the person standing next to the passenger door. It is also evident that every pixel of the same color as the bear cubs is segmented as if it were part of the object (plants and leaves in the background).

To ensure maximum objectivity and empirical grounding in the comparison, the algorithm performances were evaluated through parameters whose values are shown in Table 1. By analyzing the results, a drastic difference in performance can be seen between traditional clustering-based approaches and modern deep learning-based approaches.

Table 1: Segmentation results for the first image

Algorithm	Time (s)	Acc	IoU	Rec	Dice
K-Means	0.3441	0.59	0.48	0.78	0.65
FCM	0.7608	0.59	0.43	0.78	0.60
Mask R-CNN	4.4301	0.98	0.86	0.91	0.93

Traditional K-Means and FCM algorithms yield identical baseline accuracy scores *(Acc = 0.59)*, indicating that these methods correctly classify slightly over half of the image pixels. However, the performance disparity of pixel-intensity-based approaches becomes prominent when examining region-overlap metrics. K-Means records a restricted overlap index *(IoU = 0.48)*, whereas FCM demonstrates further performance degradation *(IoU = 0.43, Dice = 0.60)*. These quantitative results demonstrate that segmentation approaches relying exclusively on low-level color intensity features struggle to effectively resolve complex background textures.

While traditional unsupervised methods offer low computational latency *(< 1 s)*, their operational utility is limited by an inability to discriminate target boundaries amidst feature-adjacent backgrounds. In contrast, Mask R-CNN achieves robust spatial segmentation across all target instances - including vehicles, pedestrians, and wildlife - at an execution time of *4.4301 s*. This trade-off between execution speed and semantic precision highlights the suitability of deep learning architectures for real-time risk assessment in dynamic traffic environments.

The second test image captures a low-visibility forested environment, introducing severe optical and semantic challenges that test the operational bounds of each algorithm:

- Instance Closeness and Occlusion: The scene contains multiple adjacent and partially overlapping vehicles belonging to the same object class. Because pixel-clustering methods lack semantic instance awareness, they consolidate spatially continuous target pixels into a single contiguous segment. Conversely, Mask R-CNN leverages high-level region proposal networks to delineate individual instance boundaries.
- Optical Reflections and Specular Glare: Headlights from the vehicle on the left induce localized pixel saturation (intensity values approaching maximum thresholds). This optical artifact destroys gradient information along vehicle contours, causing low-level clustering techniques to misclassify high-intensity reflections. Mask R-CNN avoids this pitfall by prioritizing spatial structure and semantic geometry over raw intensity values.
- Non-Uniform Lighting and Background Homogeneity: Irregular canopy shadows create dynamic lighting gradients across vehicle surfaces. Furthermore, background vegetation shares spectral characteristics (similar hue and intensity) with target vehicles. This spectral similarity causes K-Means and FCM to frequently misallocate background regions to the foreground target classes.



Figure 4: Application of segmentation algorithms to the second image

Figure 4 illustrates the qualitative visual segmentation results obtained by comparing the ground truth masks against K-Means, Fuzzy C-Means (FCM), and Mask R-CNN across the evaluated test scenes. Clustering performed using K-Means and Fuzzy C-Means algorithms does not possess the concept of instances, and it merges all vehicles located in close proximity into one geometrically unrecognizable whole. In contrast, the visual result of Mask R-CNN segmentation perfectly corresponds with a high overlap index (*IoU = 0.92)*. The deep network successfully ignores all optical

disturbances, eliminates reflections and shadows, and generates clean and smooth binary masks. The key advantage lies in successful instance segmentation: Mask R-CNN accurately detects the boundaries between individual vehicles, enabling their successful separation and counting within the scene, thereby confirming the superiority of semantic understanding at a high level.

Table 2: Segmentation results for the second image

Algorithm	Time (s)	Acc	IoU	Rec	Dice
K-Means	0.2282	0.78	0.21	0.22	0.35
FCM	0.8522	0.78	0.21	0.26	0.35
Mask R-CNN	5.4279	0.97	0.92	0.95	0.96

K-Means and FCM yield seemingly high overall baseline values *(Acc = 0.78)*. However, evaluating spatial overlap metrics reveals a substantial divergence between simple pixel classification and true region overlap. K-Means achieves a limited Intersection over Union score *(IoU = 0.21)* and a Dice coefficient of 0.35, while FCM shows only a marginal increase in recall *(Rec = 0.26)*. This pronounced gap between high global accuracy and low region-overlap values demonstrates mathematically that unsupervised models merely segment the dominant background pixel mass while misinterpreting target boundaries. Furthermore, FCM exhibits notable computational overhead, requiring nearly four times longer processing latency than K-Means. This latency penalty stems directly from iterative fuzzy membership computations across high-resolution, texture-heavy pixel regions.

In contrast, Mask R-CNN model demonstrates strong architectural robustness. Despite scene complexity and multiple target instances, the deep learning framework maintains consistent performance across all spatial metrics *(> 0.9)*. The execution duration of *5.4279 s*, while higher than the *0.2282 s* latency of K-Means, presents a favorable trade-off given the model's capacity to extract semantically precise instance masks. Traditional unsupervised methods prove ill-suited for this scenario due to their inability to suppress high-frequency background noise from surrounding vegetation. Conversely, Mask R-CNN effectively isolates individual vehicles within the convoy, remains unaffected by headlight glare, and accurately delineates safety-critical infrastructure, offering a reliable data foundation for automated driver assistance systems.

The third test image depicts a cluttered urban intersection featuring active road workers, handheld equipment, and a dense background composed of architectural facades and vegetation:

- High-Frequency Background Clutter and Structural Detail: The scene contains extensive spatial noise, including foliage, brickwork patterns, and complex road infrastructure. Lacking contextual understanding, traditional pixel-clustering algorithms generate over-segmented, highly fragmented masks that mistakenly incorporate background building and tree textures into target object classes. Preserving semantic cohesion across fine-grained boundaries requires models equipped with high-level spatial feature extractors, such as Mask R-CNN.
- Complex Object Geometry and Tool Interactivity: Construction workers operate pavement cutters, shovels, and brooms in direct physical contact with their bodies, creating intricate geometric profiles. Furthermore, grouped pedestrians near transit stops introduce severe occlusion, making precise object boundary delineation exceptionally difficult for low-level methods.
- Instance Merging and Spatial Distortion: Due to their reliance on intensity proximity rather than structural boundaries, K-Means and FCM consistently merge adjacent individuals into singular, undifferentiated masks. In safety-critical applications, this failure to separate distinct human instances distorts spatial awareness, underestimating the exact count and physical boundaries of vulnerable road users.

A composite visual layout is presented in Figure 5, allowing an immediate comparative evaluation of target boundary adherence and noise suppression across the investigated segmentation methods.



Figure 5: Application of segmentation algorithms to the third image

K-Means and FCM experience a complete collapse of usability in such complex scenes, producing fragmented and noisy masks in which people are merged with machines/tools, and the road and background are inseparably merged with the foreground (workers). Mask R-CNN demonstrates industrial-level reliability. It extracts workers on the road with high precision despite complex working poses, recognizes pedestrians and moving vehicles, thereby enabling accurate real-time risk assessment.

Table 3: Segmentation results for the third image

Algorithm	Time (s)	Acc	IoU	Rec	Dice
K-Means	0.3423	0.78	0.11	0.32	0.20
FCM	1.1938	0.74	0.17	0.33	0.29
Mask R-CNN	4.5524	0.98	0.87	0.82	0.93

The quantitative performance metrics for the third test scenario are summarized in Table 3. The empirical findings further substantiate the intrinsic limitations of conventional clustering techniques when applied to heterogeneous urban environments. K-Means and Fuzzy C-Means (FCM) yield overall baseline accuracies of *Acc = 0.78* and *Acc = 0.74*, respectively, reflecting substantial classification challenges amidst dense background clutter. The structural fragmentation of pixel-based approaches is evidenced by region-overlap metrics: K-Means yields a restricted overlap index *(IoU = 0.11, Dice = 0.20)*, whereas FCM demonstrates only marginal improvements *(IoU = 0.17, Dice = 0.29)*. These persistent lower-bound scores confirm that unsupervised methods struggle to establish spatial cohesion across objects composed of varying spectral profiles. While K-Means exhibits minimal computational latency (*0.3423 s)* compared to Mask R-CNN *(4.5524 s)*, its degraded spatial precision limits its viability for safety-critical tasks.

Conversely, the deep learning framework effectively navigates this multi-object urban scene, maintaining balanced performance across all evaluation metrics *(Acc = 0.98, IoU = 0.87, Rec = 0.82, Dice = 0.93)*. The processing duration of Mask R-CNN represents a reasonable trade-off, as the network delivers robust, semantically accurate detection of key vulnerable entities and infrastructure within active construction zones.

Synthesizing the experimental findings, combining quantitative metrics with qualitative mask topology, highlights fundamental performance trade-offs between traditional clustering and deep learning approaches. Conventional unsupervised techniques, such as K-Means and Fuzzy C-Means (FCM), exhibit marked vulnerability under real-world operational constraints. Factors such as high-frequency texture noise, specular reflections, dynamic backlighting, and spectral overlap cause

substantial spatial fragmentation and severe degradation in region-overlap precision. Although K-Means retains low computational latency on simpler geometries, FCM incurs a disproportionate computational overhead when processing high-resolution images featuring complex spatial transitions. Conversely, Mask R-CNN demonstrates strong architectural resilience and superior semantic understanding of high-level visual context. The model effectively mitigates optical artifacts and intricate scene geometries, yielding high-precision instance masks at predictable execution times. These findings validate the necessity of deep convolutional networks for modern computer vision tasks in dynamic environments. Ultimately, replacing pixel-level intensity heuristics with instance-aware semantic segmentation enhances the operational reliability of autonomous perception systems. Where low-level clustering risks hazardous false negatives - such as failing to delineate vulnerable road users or construction personnel - Mask R-CNN provides a robust spatial foundation suitable for time-sensitive active safety interventions. [10]

5. CONCLUSION

In this paper, a comprehensive comparative analysis of the performance of traditional low-level clustering-based algorithms (K-Means and Fuzzy C-Means) and a modern, robust deep learning-based model (Mask R-CNN) was conducted, thereby successfully implementing and evaluating an advanced system for semantic segmentation aimed at increasing the safety of humans and the environment. Through a comparative analysis on three highly demanding test scenes from the COCO dataset, it was demonstrated that traditional clustering algorithms do not possess the necessary robustness to lighting anomalies, complex backgrounds, and low contrasts characteristic of real-world traffic and industrial environments.

Regarding the scientific hypothesis, the experiment confirmed the superiority of the high-level semantic approach. While traditional algorithms achieved critically low overlap indices (IoU ≈ 0.11–0.48), Mask R-CNN offers exceptional robustness through a stable range (IoU ≈ 0.86–0.92) regardless of scene complexity. In this way, the technological and conceptual gap between traditional unsupervised methods and modern deep convolutional networks has been demonstrated.

Furthermore, the results highlight the inherent limitations of spectral segmentation. It has been shown that relying solely on the spectral intensity and color of individual pixels makes K-Means and FCM systemically non-robust. The result of these methods is morphological mask fragmentation, an inability to recognize multiple objects of the same class, and a complete lack of the instance segmentation concept for closely spaced objects, whereas a deep learning model like Mask R-CNN completely ignores color, relying on the shape of the given class.

The contribution of this work is reflected in the clear demonstration of the evolution of image segmentation methods and the mapping of the limits of applicability of individual technologies with the aim of protecting humans and the environment. Although K-Means and FCM are applicable in controlled, industrial conditions with uniform lighting and homogeneous objects, they are completely inadequate for complex, dynamic scenes from the real world where lost time cannot be recovered. As a natural continuation of this research, future work should focus on optimizing deep models by testing the developed models under extreme weather conditions (dense fog, heavy snow, downpour) to further confirm the robustness of the system in all ambient conditions. Additionally, the application of technologies such as *NVIDIA TensorRT* and model quantization (converting FP32 to INT8 precision) would enable the execution of models directly on embedded systems within vehicles and industrial cameras with a refresh rate of > 30 fps.

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Professional paper

CAUSES OF ACCIDENTS AND PROTECTION MEASURES WHEN WORKING WITH CONVEYORS

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Abstract: *A large number of accidents occur when working with conveyors. Such accidents are regularly followed by injuries, sometimes fatalities, when working on conveyors and around conveyors. The causes of injuries while working with conveyors can be different. They are the following: dangers of getting stuck and entanglement; slips, trips and falls around conveyors; falling loads; electrical and mechanical defects; injuries from manual handling; lack of emergency stops and safety training; inadequate protection and access control; maintenance-related hazards and others.*

Statistical data for the period from 2011 to 2015 and period from 2015 to 2024 are analyzed and presented, which indicate the possible dangers and the type of most common injuries when working with conveyors. Also, protective measures for working on and around conveyors are analyzed.

Based on that, they are defined rules and regulations for the operation of conveyors. They should respect the employees who operate the conveyors and those who work and move near them.

Key words*: Conveyors, accidents, causes of injuries, protection measures.*

INTRODUCTION

In recent years, conveyor belts and similar systems have increased in popularity, especially in workplaces such as factories, warehouses, mines, and department stores. These belt systems do wonders to increase productivity and efficiency, but that does not mean they are 100 percent safe or free of risk–a large number of workers are injured in conveyor belt accidents each year.[1]

These systems are no different from any other type of machinery in that they must be installed, maintained, and operated properly to ensure the safety of workers. In addition, the workers themselves must be properly trained and supervised when working so that they know how to spot and deal with potential hazards as they arise. Otherwise, disaster can occur, [2]

The injuries sustained in conveyor belt accidents are often severe and sometimes fatal, which is why employers should have safety measures in place to protect their employees.Some of the most common causes of conveyor belt accidents are:Lack of guards or poor assembly) Excessive speed, (Defects or lack of maintenance, A lack of lockout and tagout procedures, Overloads, Inadequate training .

The U.S. Department of Labor Bureau of Labor Statistics reports over fifty workplace fatalities a year where conveyors are the primary source of injury. Workplace injuries account for nearly 25% of all workers' compensation claims and up to 35% of all associated costs.[3]

The risk of conveyor belt injuries, particularly the danger of getting an arm caught in the machinery, is a serious hazard that requires proactive measures to prevent. Implementing comprehensive safety protocols, conducting regular maintenance, providing thorough training, and fostering a safety culture are essential steps to mitigate these risks and protect workers.[4]

1. TYPES OF ACCIDENTS WHEN WORKING WITH CONVEYORS

According to the US Bureau of Labor Statistics, each year in the USA nearly 9,000 workers get injured and 40 workers die in conveyor belt accidents. On the other hand, the Health and Safety Executive (HSE) reports state that the food and drinks industry alone is responsible, for over 30% of fatal injuries from a rubber conveyor belt.[5]

1.1. Entanglement Hazards

A conveyor system has many moving parts like the belts, pulleys, and rollers. Hair, loose clothes, and even body parts of the workers can get entangled in these moving parts of the rubber conveyor belt system. This can result in serious injuries, including amputations or fatalities.

Prevention:

- Can be installed fixed guards with viewing windows over moving parts of the rubber for conveyor belt to prevent contact.
- Employees should be educated about the dangers of entanglement and strict protocols should be implemented to keep hands, clothing, and tools away from moving components.

1.2. Amputation, or Severe Lacerations at Pinch Points

Pinch points in rubber belting are the places where two machine parts move together. These are the places where the workers get wounded the most. If their fingers or hair gets stuck here, the person may suffer from serious injuries or even die.

Prevention:

- It is recommended to use barriers such as fences to protect pressure points, especially near conveyor rollers and pulleys.
- Danger areas should be clearly marked and to conduct regular safety checks.

1.3. Shear points in a conveyor system Wound at Shear Points

They are created when the edges of two machine parts move across or close to each other. The tremendous force here can cut any material and even body parts.

Prevention:

- Shear points should be protected with appropriate guardrails to prevent accidental contact.
- Need timely maintenance - regular inspection of guardrails to confirm they are safe and in good condition.

1.4. Hit by Material Spillage

A rubber conveyor belt moves at a great speed. Therefore, spillage does not only cause accidents but also significant material loss. It is also one of the 7 most reported problems by conveyor belt users.

Prevention:

- It is recommended to avoid overloading conveyors.
- Nets or barriers should be installed to collect falling materials.

1.5. Slips, Trips, and Falls

Slips, trips, and falls are common in workplaces where there are extreme environmental conditions, chemical factories, and oil refineries. Spilled materials or obstructions around conveyor areas can lead to slip and trip hazards.

Prevention:

- Identification of such areas is required **-**If the workplace has slippery areas, they should first be identified and put up warning boards.
- Maintain clean work areas by promptly cleaning spills and removing debris.

1.6. Electrical Hazards

Heavy duty rubber conveyor belt systems run on critical electrical components. Therefore, workers should be protected from such hazards.

Safety Tips:

- Personal protective equipment such as electrical safety grounding should be used near high-voltage system components. An electrical mat is an electrical insulator- a useful component that protects the workers from electric shock. Similarly, there are other types of electric insulators like gloves, jackets, etc.
- Qualified personnel required **-**Only trained and authorized personnel perform electrical maintenance.

1.7. Lockout/Tagout (LOTO) Failures

Inadequate LOTO procedures (a situation where adequate safety procedures are not followed; such as isolating the belt's power source before rubber conveyor belt maintenance or repair work) can lead to accidental startups, causing injuries.

Prevention:

- Strict LOTO protocols required- To Implement and enforce comprehensive LOTO procedures during maintenance.
- Training: Regular training of employees on LOTO practices is recommended to ensure compliance.

1.8. Misaligned Materials From Overloading

Exceeding the conveyor's load capacity can cause mechanical failures, leading to accidents.

Safety Tips:

- The manufacturer's recommendations should be followed.
- Smart Monitoring Systems It is recommended that sensors be used to detect and prevent overload.

1.9 Fire and Explosion

A rubber conveyor belt runs continuously. Thus, it generates heat due to friction. This can lead to fires or explosions in industries handling combustible materials like coal, grain, or chemicals. Moreover, electrical faults and overheated rollers also contribute to fire hazards in a heavy duty rubber conveyor belt.

Prevention Tips:

- Fire-retardant belts should be used**:** Fire-resistant rubber conveyor belts can be chosen in high-risk industries.
- Fire suppression systems -Conveyor areas should be equipped with fire detection and automatic suppression systems.

1.10. Dust Accumulation and Respiratory Hazards

Fine dust generated from conveyed materials can pose both respiratory risks to workers and increase fire hazards. Excessive dust buildup also affects rubber conveyor belt performance.

Safety Tips:

- Dust Control Systems: It is recommended to use dust extraction and suppression systems to minimize airborne particles.
- Personal Protective Equipment (PPE) - Workers should be provided with respirators and enforce PPE use in high-dust areas.

2. CONVEYOR INJURIES STATISTICS AND DISCUSSION

Injuries while working with conveyors and injuries in general have a negative impact on a country's economy. For this purpose, they will be analyzed statistical data on injuries while working with conveyors in the world and in our country. [6]

The following data is intended to help operators better understand the occupational safety hazards associated with conveyors.

Data on nonfatal and fatal injuries related to conveyor belts from 2011 to 2015 from the U.S. Bureau of Labor Statistics is analyzed. These statistics provide information on how, where, and why these incidents occurred.

2.1 Body parts impacted by belt conveyor injuries

Analysis of BLS data shows that injuries to the upper body and upper extremities are most common body parts hurt in incidents. Of the lower extremities, knees are the most at-risk body part when working with belt conveyors.

The following diagram shows the average number of injuries/year by specific body parts for the period 2011-2015.[7]

The values are given as the average value of injuries per year for the period 2011-2015 (Average incidents per year calculated from BLS data by Powder & Bulk Solids)

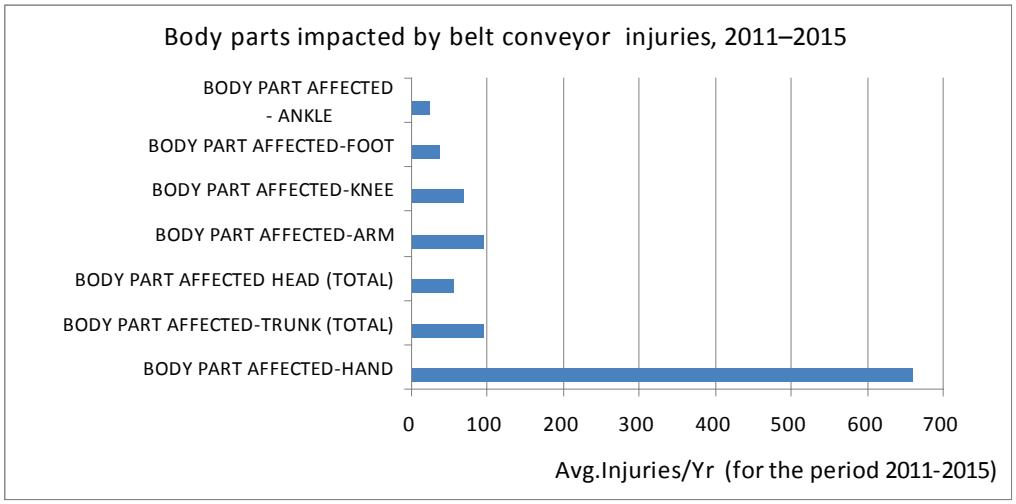


Figure 1: Body parts impacted by belt conveyor injuries, for tha period 2011–2015 (Data source: U.S. Bureau of Labor Statistics (BLS), 2011–2015.)

2.2 Top five Occupations of belt conveyor injuri victims

Workers in transportation, material moving, and production occupations are at the highest risk for belt conveyor-related injuries, according to Bureau of Labor Statistics data.

Nearly one third of the 6080 belt conveyor-related injuries in the U.S. recorded by the BLS from 2011 to 2015 impacted workers in transportation and material moving occupations (31.43%, or 1880 incidents). During that period, over a quarter (28.76%, or 1720 incidents) of injury victims worked inproduction jobs.[1]

The following graph Fig.2 will present the five occupations where these injuries are most common.

The values are given as the average value of injuries per year for the period 2011-2015 (Average incidents per year calculated from BLS data by Powder & Bulk Solids)[7]

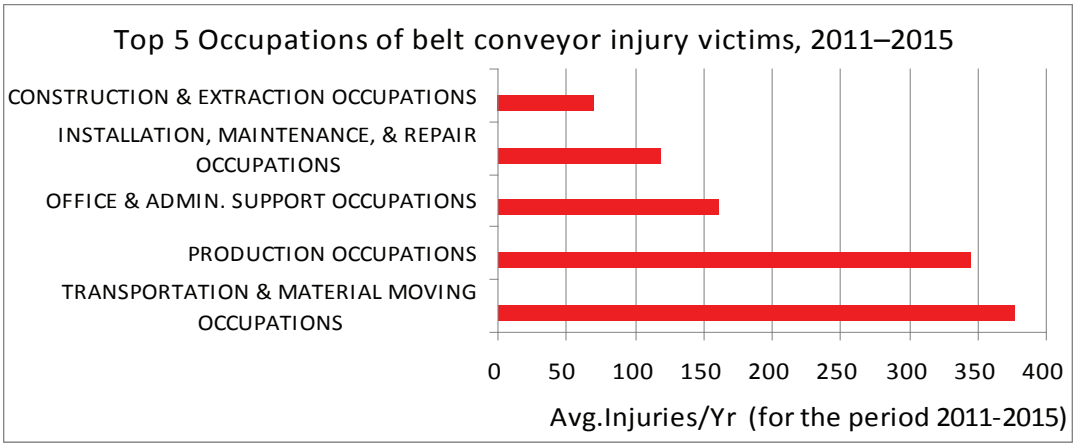


Figure 2: Top five Occupations of belt conveyor injuri victims, for tha period 2011–2015 (Data source: U.S. Bureau of Labor Statistics (BLS), 2011–2015.)

3. INJURIES WHILE WORKING WITH CONVEYOR BELTS IN THE EU

In Europe, there are no complete statistics on injuries from conveyor belts alone, but available reports show that conveyors were among the most common sources of serious industrial injuries and deaths.

Between 2011 and 2015, conveyor-related injuries in European industrial environments were predominantly related to maintenance and cleaning activities, and not with equipment failure.

Conveyor systems participated for approximately 30% of machinery-related injuries in the food and manufacturing industries, with flat belt conveyors representing the highest risk configuration.[8] The majority of injuries occur from entrapment and crushing at the entrapment points. They often result in serious injuries, including amputations.

Conveyor systems present a unique hazard profile characterized by entrapment and entanglement injuries, particularly during maintenance operations, whereas forklifts and presses exhibit higher fatality and instantaneous trauma rates due to kinetic impact and high-force compression mechanisms [6].

The comparative risk classification is based on synthesis of findings from EU-OSHA, HSE (UK), OSHA and ILO reports on machinery-related occupational injuries.“

Data on conveyor belt injuries in Europe (2015–2024) is based on HSE, EU-OSHA and Eurostat analysis.

The EU does not have separate statistics just for "conveyor belts", so the data is kept as part of "machinery accidents".The following diagram will present the part of conveyors in machine injuries in EU/UK .[9][10]

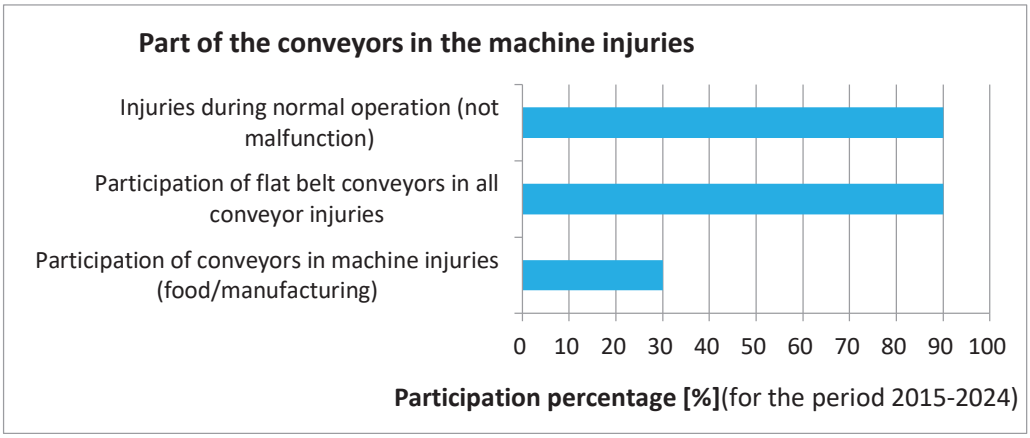


Figure 3: Part of the conveyors in the machine injuries (EU/UK) 2015–2024

Between 2015 and 2024, conveyor systems remained one of the leading sources of machinery-related occupational injuries in European industrial environments. HSE-based analyses indicate that conveyors account for approximately 30% of machinery accidents in food and manufacturing sectors, with the majority of incidents occurring during routine operations such as cleaning, blockage removal, and maintenance. Flat belt conveyors represent the highest-risk configuration, responsible for up to 90% of conveyor-related injuries, primarily due to entrapment at in-running nip points.

Conveyor accidents persist in Europe because the risk is not primarily caused by equipment failure, but by routine human interaction with hazardous moving parts under operational pressure.

4. SAFETY AND PROTECTION MEASURES WHEN WORKING WITH CONVEYORS

In the United States, conveyor belt safety is governed by the Occupational Safety and Health Administration (OSHA).OSHA standards define the minimum safety requirements for machinery, equipment, and processes. Regarding conveyor systems, these regulations aim to:Prevent mechanical injuries, Ensure safe maintenance practices and Promote hazard awareness.[11]

In addition to OSHA requirements, conveyor systems are also guided by industry-specific standards established by the Conveyor Equipment Manufacturers Association (CEMA) which provides standardized technical guidelines and best practices for the design, construction, operation, and maintenance of conveyor systems.

CEMA places a strong emphasis on safety through several key design and operational recommendations, including: Installation of protective guarding around moving parts, Proper belt tracking to avoid misalignment and spillage, Easy and safe access for maintenance activities, Noise

and dust control to protect workers and comply with regulations, Integration of emergency stop devices and safety signage.

CONCLUSION

Analysis of statistical data on the number of injuries when working with conveyors shows that they are high. Which also brings to an increase in the costs of injuries.

According to the US Bureau of Labor Statistics and European statistics, information is provided on how, where and why these incidents occur. Also what type of injury occurs.

Analysis of the data shows that injuries to the upper body and upper extremities are the most common parts of the body injured in incidents. And that's mostly hand injuries presented in Fig.1. Workers in transportation, material moving, and production occupations are at the highest risk for belt conveyor-related injuries, according to Bureau of Labor Statistics data, Fig.2. In Europe, there are no complete statistics on injuries from conveyor belts alone, but available reports show that conveyors were among the most common sources of serious industrial injuries and deaths. But analyses show that between 2015 and 2024, transport systems remained one of the leading sources of machinery-related workplace injuries in European industrial environments, Fig.3.

Therefore, it is necessary to make a precise categorization of injuries when working with conveyors, in order to take appropriate specific protective measures. All in accordance with the Occupational Safety and Health Administration (OSHA) and the Conveyor Equipment Manufacturers Association (CEMA). This will reduce the number of injuries when working with conveyors and possible elimination.

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Professional paper

QUALITY REPRODUCTION CYCLE AS A SOURCE OF BUSINESS IMPROVEMENT

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Abstract: *This paper analyzes the quality reproduction cycle as an instrument for improving business performance. Using a conceptual and professionally oriented approach based on relevant literature, practical experience, and illustrative analysis, the paper examines how quality affects the main phases of the reproduction cycle and key business indicators, including productivity, efficiency, and profitability. The analysis indicates that deviations from quality requirements may increase costs, reduce process efficiency, and cause economic losses. It is concluded that systematic management of quality throughout the reproduction cycle can support the more efficient use of resources, improve business performance, and contribute to the long-term competitiveness of enterprises.*

Keywords: *Quality reproduction cycle, business improvement, productivity.*

1. INTRODUCTION

The concept of reproduction is primarily rooted in economics. It originated from the simple principle of “money–commodity–money”. Considering its significance in process and business management, reproduction can be viewed and analyzed from various perspectives.

In this paper, reproduction is considered from the perspective of the quality reproduction cycle. The quality of materials, raw materials, components, semi-finished products, finished products, packaging, and other inputs can significantly influence the quality of process outputs. Depending on the achieved level of quality, these elements may contribute to increased process performance and value creation or, conversely, reduce the economic value generated by the process.

In the context of this approach, the quality reproduction cycle is presented as a potential source of business improvement. Quality is becoming increasingly important in all aspects of business operations, as the production of low-quality products and services generates significant costs and negatively affects organizational performance. Therefore, quality can be observed as an integral part of the enterprise reproduction cycle and as one of the key factors influencing business success.

The objective of this paper is to demonstrate the importance of the quality reproduction cycle as a source of business improvement. In addition to providing a theoretical overview of the concept, the paper presents practical examples and recommendations for its application in modern market conditions.

Modern quality management systems, particularly those based on ISO 9001:2015 [1] requirements, emphasize process effectiveness, risk-based thinking, and continual improvement as essential factors for achieving sustainable business success. This approach is also relevant to occupational safety and health, since risk-based thinking, employee competence, process reliability, and preventive management contribute not only to product and service quality but also to safer working conditions.

2. RESEARCH METHODOLOGY

This paper is based on a theoretical and practical analysis of the quality reproduction cycle as an instrument for business improvement. The research methodology includes the analysis and synthesis of relevant literature in the fields of quality management, business economics, and business process management. In addition to theoretical sources, practical experience gained through the implementation of quality management systems, the conduct of internal and external audits, and the realisation of business improvement projects in various organisations was also utilised.

The study is based on a descriptive and analytical approach aimed at examining the impact of quality on individual phases of the reproduction cycle and their influence on business performance. Particular attention is given to the analysis of the relationship between quality and productivity, efficiency, profitability, and competitiveness, as well as to the identification of potential sources of business improvement.

The proposed model was developed through the synthesis of theoretical knowledge, professional experience, applicable national and international requirements, market conditions, and modern quality management principles. It represents a conceptual framework for assessing the maturity of business management practices and identifying opportunities for continual improvement in organisational performance.

The practical examples, percentages, and indices presented in the paper are illustrative and model-based. They are used to demonstrate the application of the proposed approach and should not be interpreted as empirical findings obtained from a specific organisation. No additional empirical data collection was conducted for the purposes of this paper.

3. ELEMENTS OF THE REPRODUCTION CYCLE

In addition to the previously presented definitions, reproduction can also be defined as the continuous renewal of the production process. Reproduction is essential for both the qualitative and quantitative development of processes, as it enables the uninterrupted continuation of production activities. Within the production process, reproduction may involve the production of means of production, goods intended for personal consumption, and goods intended for general use or consumption.

There are three basic forms of reproduction:

- Simple reproduction – the renewal of production at the same scale, without significant growth;
- Expanded reproduction – the renewal of production accompanied by an increase in production volume, innovation, capital growth, and production modernization;
- Reduced reproduction – the renewal of production at a reduced scale due to unfavourable conditions, economic disturbances, or crises.

Regardless of the form of reproduction applied, quality plays a crucial role. Any deviation from specified requirements may significantly reduce process performance, decrease efficiency, and generate economic losses.

The main elements of the reproduction cycle are production, distribution, exchange, consumption, and reinvestment. Each of these elements can be analysed from the perspective of quality, usability, and the efficient utilisation of resources. The significance of this approach becomes particularly evident when examining the flow of the reproduction cycle and the various quality-related outcomes that may occur throughout its different stages.

3.1. Importance of the Quality Reproduction Cycle for Business Performance

Modern business is characterised by a dynamic environment in which organisations must continuously seek ways to improve their efficiency, productivity, and competitiveness. One of the key concepts that enables sustainable growth and development is the quality reproduction cycle. High-quality business operations support the continuous renewal of activities, the growth of production and services, and the improvement of resources and capital.

Since quality is achieved through all organisational processes, the quality reproduction cycle encompasses all stages of business operations, including the provision of financial resources, procurement, storage, production, distribution, and other related activities.

The quality reproduction cycle enables organisations to achieve:

- Rational utilization of resources;
- Reduced operating costs;
- Increased production volume;
- A stable flow of revenue and profit.

By ensuring the efficient use of resources, reducing business costs, and enhancing competitiveness, the quality reproduction cycle contributes directly to improved organisational performance. Modern quality management approaches emphasise the need to consider quality throughout the entire product life cycle, from design and production to use and customer feedback [2].

4. THE REPRODUCTION CYCLE IN BUSINESS FROM THE QUALITY PERSPECTIVE

The impact of quality is evident in every stage of the reproduction cycle. Through its influence on individual activities and processes, quality affects process and product performance, efficiency and effectiveness, productivity, profitability, and economic efficiency, as well as the ability to meet customer requirements and optimise the utilisation of resources. Based on these considerations, it is possible to refer to a so-called “quality mix”. Quality can be measured in both absolute and relative terms (against established standards or competing products), assessed objectively and subjectively, and used as a basis for the classification of products and materials. Furthermore, changes in quality levels may directly influence the value generated throughout the reproduction cycle.

The overall reproduction cycle can therefore be analysed from the perspective of quality. Such an analysis may reveal weaknesses, inefficiencies, sources of waste, and ultimately economic losses. Consequently, the implementation of quality management systems generates not only operational and organisational benefits but also significant economic effects that contribute to improved business performance.

The presented model identifies six global segments and sixteen possible outcomes that can be used to evaluate the effects of quality, determine quality-related losses, and define the necessary corrective, preventive, and improvement measures. Through this approach, organisations can systematically assess the impact of quality on business processes and identify opportunities for increasing productivity, reducing costs, and improving overall competitiveness.

The presented cycle can be interpreted as follows:

- Financial resources are utilized in proportion to their available value, regardless of the currency in which they are expressed.
- Deliveries from suppliers, including raw materials, components, and other production inputs, may fully satisfy quality requirements (e.g., 80%, 88%, 90%, or higher conformity levels) or fail to meet them entirely. Depending on the degree of compliance with quality requirements, the resulting process performance may generate the expected value or, conversely, lead to losses and damages.
- Materials held in inventory may have a similar impact on process outputs as the materials supplied directly by suppliers. Their quality level directly influences the effectiveness and efficiency of subsequent production activities.
- Work-in-progress resources, primarily consisting of semi-finished products, raw materials, and components, may fully comply with specified requirements, partially comply, or fail to comply altogether. These quality levels are directly associated with productivity, economic efficiency, equipment utilisation, resource consumption, process quality, and the value of final outputs.

- Finished products are directly affected by their quality level. Products may be sold at their full market value, sold at discounted prices, or become unsellable due to quality deficiencies, resulting in financial losses for the organisation
- Resources at the customer stage represent the financial assets generated through product sales. At this stage, organisations may experience timely and full payments, delayed payments, partially recoverable receivables, or complete losses resulting from customer insolvency, bankruptcy, or business discontinuation.

Each stage of the reproduction cycle demonstrates that product quality, product price (through the impact of quality-related costs), and delivery time (through the impact of quality on productivity) are among the most critical factors influencing business success. Consequently, effective quality management throughout the entire reproduction cycle is essential for achieving operational excellence, customer satisfaction, and long-term organizational sustainability.

4.1. Sources of Improvement and Improvement Activities

A sample calculation performed on a model company ("XX") showed that, across all six stages of the reproduction cycle and sixteen possible output scenarios, deviations from quality requirements resulted in annual losses equivalent to approximately two gross employee salaries. This amount represented 5.4% of the company's total operating expenses.

As a consequence of reduced productivity, the value of production decreased by 8.7%, while the overall business effects declined by 11.5%. The overall quality level achieved was 89.1%, whereas the business reliability index amounted to 8.87%. From an economic perspective, the increase in operating expenses by 5.4% corresponds to a reduction in the profit rate of approximately 5–6%.

Furthermore, analyses conducted in micro, small, and medium-sized enterprises indicate that the average profit rate is approximately 6.4%. The close correlation between these indicators provides additional evidence of the significant impact that quality has on productivity, efficiency, profitability, liquidity, competitiveness, operating costs, and ultimately on overall business performance and organizational success.

These findings confirm that quality should not be viewed solely as a technical characteristic of products and services, but rather as a strategic business factor that directly influences economic performance. Consequently, the systematic monitoring of quality throughout the reproduction cycle enables organizations to identify improvement opportunities, reduce losses, optimise resource utilisation, and strengthen their competitive position in the market.

5. MODEL FOR THE DEVELOPMENT OF A MODERN BUSINESS MANAGEMENT APPROACH

Effective quality management and the management of reproduction cycles (quality-related, economic, and other types of cycles) require an appropriate level of managerial knowledge, competencies, and skills that correspond to modern management principles. Each organisation should assess its current level of managerial capability, identify its position in relation to best practices, and define the necessary measures and improvement activities required to achieve higher levels of performance.

The increasing complexity of business environments, market requirements, technological development, and regulatory obligations requires organisations to continuously improve their management approaches. In this context, successful management of reproduction cycles depends not only on operational control but also on the ability to integrate knowledge, experience, regulatory requirements, market expectations, and modern management tools into a coherent management system.

To support this objective, the authors propose the following model for the development of a modern business management approach. The proposed model represents a conceptual framework for assessing organisational management maturity and identifying opportunities for continuous improvement. It combines traditional management knowledge with modern methods, techniques, regulatory requirements, market influences, and practical experience, providing a structured basis for improving business performance and achieving sustainable organizational success.

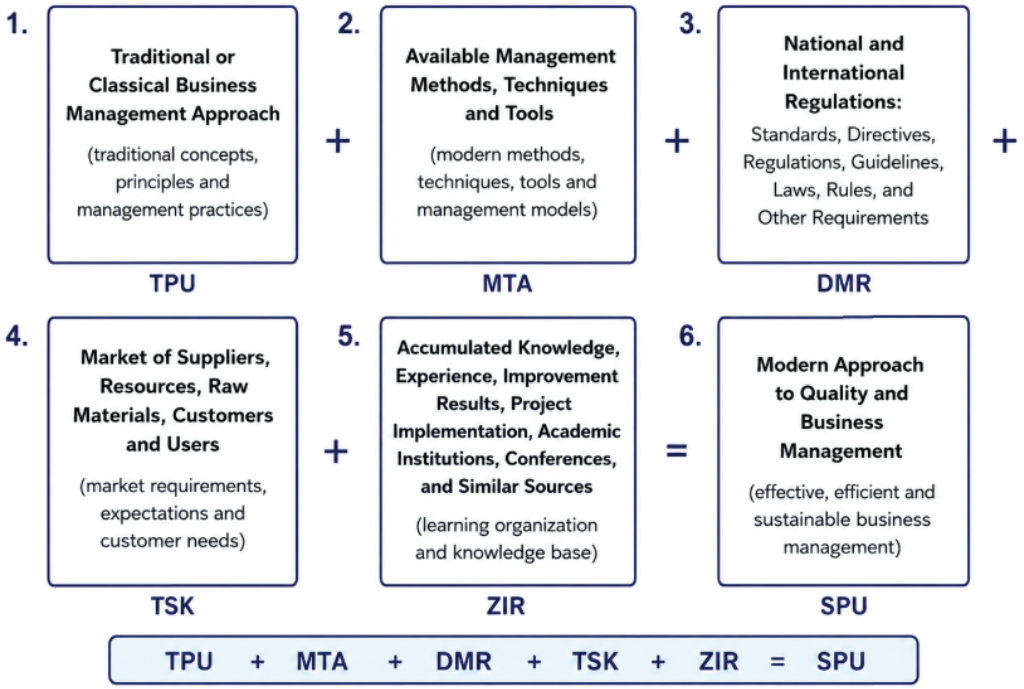


Figure 1: Proposed Model for the Development of a Modern Business Management Approach [3]

Managing reproduction cycles is a highly complex activity, as they are essential for organizational sustainability and growth. They influence financial stability and liquidity, enable resource optimization, and may generate risks if not properly managed. At the same time, they provide a basis for defining future perspectives and business strategies and represent an important source of business improvement. The development of a modern business management approach can be expressed through the following model:

TPU+MTA+DMR+TSK+ZIR=SPU, where:

Table 1: Elements of the Model for the Development of a Modern Business Management Approach [3]

Element	Description
TPU	Traditional Business Management Approach
MTA	Management Methods, Techniques and Tools
DMR	National and International Regulations
TSK	Market of Resources, Suppliers and Customers
ZIR	Knowledge, Experience and Implementation of Activities
SPU	Modern Approach to Quality and Business Management

The presented model integrates key elements that influence the development of a modern business management approach [3]. By combining traditional knowledge, modern management methods, regulatory requirements, market expectations, and accumulated experience, the necessary conditions are created for more effective process management and the achievement of improved business performance. The model may serve as a framework for assessing the maturity of management systems and identifying directions for future improvement.

The modern approach to business management involves the application of various methods, techniques, and tools, such as Lean Management, Six Sigma, Lean Six Sigma, the Theory of Constraints (TOC), and Total Quality Management (TQM), all of which contribute to improving process efficiency and enhancing the quality of products and services [4].

5.1. Risks in Managing Reproduction Cycles

The management of reproduction cycles involves the continuous planning, implementation, control, and improvement of business activities. Various risks may arise throughout different phases of the reproduction cycle and negatively affect product and service quality, productivity, profitability, and overall business performance. Therefore, risk identification, assessment, and treatment represent essential elements of modern quality management systems [5]. Risks may occur in procurement, production, storage, distribution, and market-related activities, resulting from nonconforming inputs, equipment failures, delivery delays, changing customer requirements, or economic disturbances. Human resources also represent a significant source of risk, as employee competence, motivation, communication, and involvement directly influence process effectiveness and the achievement of organizational objectives [6]. Modern management systems are based on preventive actions and risk-based thinking, while the PDCA cycle is recognized as one of the most important tools for continual improvement, systematic problem-solving, and effective risk management [7].

6. CONCLUSION

The reproduction cycle in economics and quality management represents an important instrument for business operations. Quality and economics are two interrelated concepts, and when effectively managed, they contribute significantly to organizational success. The quality reproduction cycle plays a crucial role in ensuring business sustainability, growth, and development. It influences financial stability and liquidity while identifying opportunities for resource optimization, cost reduction, profitability improvement, and innovation. Furthermore, it provides a basis for effective planning and can be regarded as an important source of business improvement.

The analysis conducted in this paper confirms that quality is not merely a technical issue related to product and service conformity but also a key factor influencing organisational economic performance. The proposed model for the development of a modern business management approach demonstrates that successful management of reproduction cycles requires the integration of traditional knowledge, regulatory requirements, market needs, and accumulated experience into a unified management system.

From the perspective of occupational safety and health, the proposed approach highlights the importance of competent employees, reliable processes, systematic risk management, and preventive action. The integration of these elements into business processes can contribute to safer working conditions, fewer operational disruptions, and more sustainable organisational performance.

The results of this study may serve as a basis for future research focused on quantifying the economic effects of quality and developing models for measuring the impact of reproduction cycles on organisational performance. The proposed model has a conceptual character and should be further validated through empirical research conducted in organisations of different sizes and sectors.

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Professional paper

PROTECTIVE DEVICES IN ELECTRICAL INSTALLATIONS: APPLICATION AND PREVENTIVE MAINTENANCE AS AN OCCUPATIONAL SAFETY MEASURE

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Abstract: *Protective devices play a key role in preventing electrical accidents, equipment damage, and fires. This paper reviews fuses, circuit breakers, residual current devices, surge protective devices, arc-fault detection, thermal monitoring, and cabinet fire-suppression systems. It also connects the international standards framework with Croatian occupational safety and fire-protection obligations. Special emphasis is placed on regular inspection, testing, and maintenance to preserve the reliability of protective functions throughout the installation life cycle. Preventive maintenance supports timely fault detection, reduces workplace risk, and strengthens both worker safety and electrical-system reliability.*

Keywords: *Electrical installations, protective devices, preventive maintenance of protective devices, worker safety*

1. INTRODUCTION

Electricity is an indispensable energy carrier in modern workplaces, but it remains a serious source of occupational risk. The main hazards include electric shock and burns from contact with live parts, arc injury, fire caused by faulty equipment or installations, and ignition of explosive atmospheres [1, 2]. Protective devices are therefore not only components of an electrical design; they are preventive occupational safety barriers whose performance must be preserved during the whole life of the installation.

The scale of the problem remains measurable even in mature regulatory systems. U.S. Bureau of Labor Statistics data recorded 130 fatal occupational injuries from exposure to electricity in 2024 [26]. Although national reporting systems and industrial structures differ. Figure 1 illustrates the persistent workplace risk and supports continued investment in coordinated technical protection and preventive maintenance.

The technical basis for low-voltage installations is commonly built around the IEC 60364 series, especially the parts that address protection against electric shock, selection and erection of protective

equipment, and verification [3, 4, 5]. In practice, these requirements are translated into coordinated layers of protection: basic insulation and enclosures, protective earthing and bonding, automatic disconnection of supply, overcurrent protection, residual current protection, surge protection, safe isolation, and documented inspection and testing. The occupational safety value of such devices depends on correct selection and on preventive maintenance that detects deterioration before a dangerous failure occurs.

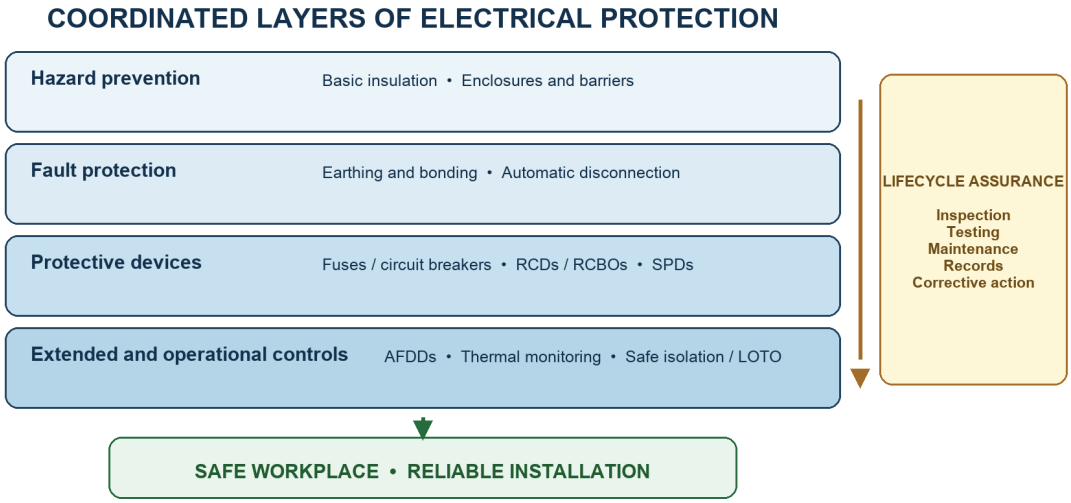


Figure 1: Coordinated layers of protection in electrical installations (authors' illustration)

2. PROTECTIVE DEVICES IN ELECTRICAL INSTALLATIONS

2.1. Overcurrent protective devices

Fuses and circuit breakers protect conductors and equipment against overloads and short circuits by interrupting currents that exceed the thermal or electrodynamic capability of the circuit. Fuses are simple, current-limiting devices whose operating characteristics are determined by the fuse link and its application category [6]. Miniature and moulded-case circuit breakers provide resettable protection, but their use must still match rated current, prospective short-circuit current, breaking capacity, selectivity and the conductor cross-section [7]. Incorrect rating or poor coordination can leave a circuit energized during a fault, produce excessive let-through energy, or cause unnecessary tripping that encourages unsafe bypassing.

2.2. Residual current protective devices

Residual current devices (RCDs) and residual current circuit breakers with overcurrent protection (RCBOs) detect an imbalance between live conductors and disconnect the circuit when residual current exceeds the rated value. They are particularly important where the fault current may be too low to operate a fuse or circuit breaker quickly enough, for example in TT earthing systems or in damp and outdoor working conditions. Devices with a rated residual operating current not exceeding 30 mA are widely used as additional protection against electric shock, while devices with a higher rated residual operating current (typically 300 mA, and therefore lower sensitivity) may be selected for fire protection or selective upstream disconnection, subject to the installation design and applicable requirements [4, 8, 9].

RCDs are not universal protective devices. They do not replace overcurrent protection, they do not protect a person who touches line and neutral simultaneously, and incorrect selection of Type AC, A, F or B devices can be problematic where power electronics produce pulsating or smooth DC residual currents. The choice of RCD type should therefore follow the loads, earthing system, manufacturer data and applicable installation and product standards [4, 8, 9, 25].

2.3. Surge protection and special protective functions

Surge protective devices (SPDs) limit transient overvoltages caused by lightning effects, network switching or faults. Their effectiveness depends on correct Type 1, Type 2 and Type 3 coordination, short connection leads, suitable earthing and bonding, and compatibility with the expected discharge current and system voltage [11, 12]. In workplaces that rely on automation, process control, information systems or medical and laboratory equipment, SPD failure may create both safety and continuity risks. Complementary functions such as isolation devices, emergency switching and insulation monitoring in IT systems complete the protective concept for specific environments [4, 13]. Fire-oriented extensions are addressed separately in Section 2.4.

2.4. Arc-fault detection, thermal monitoring and cabinet fire suppression

In installations where fire risk is significant, protective strategy can be extended beyond conventional overcurrent and residual current protection. Arc-fault detection devices (AFDDs) analyse the current and voltage waveform and disconnect final circuits when patterns typical of dangerous series or parallel arcing are detected. This is important because loose terminals, damaged conductors or carbonised insulation may produce local heating and ignition without generating a current high enough to operate a fuse or circuit breaker quickly. AFDDs are therefore an additional fire-prevention measure, not a substitute for short-circuit, overload or residual current protection [15, 16].

Automatic extinguishing devices for electrical cabinets also exist, most commonly as pre-engineered local application systems using clean agents, inert gases or condensed aerosol generators. They are intended to detect and suppress an incipient fire inside a closed switchboard or control cabinet before it spreads to the workplace. Their use should follow a fire-risk assessment, compatibility with electrical equipment, manufacturer approval, safe release criteria and national fire-protection requirements. Such systems reduce damage after ignition has started; they do not remove the need for correct design, tightening of terminals, thermographic inspection, load balancing and replacement of defective protective devices [17, 18].

Table 1: Overview of protective devices and preventive maintenance focus

Device group	Main controlled hazard	Application focus	Preventive maintenance focus
Fuses	Short circuit and overload	Rated current, voltage, breaking capacity, selectivity and replacement only with correct type.	Visual check, heat damage, tight contacts, correct spare fuse links and documentation of replacements.
Circuit breakers	Overload, short circuit and switching duty	Time-current curve, prospective short-circuit current and conductor protection.	Functional operation, condition of terminals, thermography where justified, trip-test programme for larger breakers.

Device group	Main controlled hazard	Application focus	Preventive maintenance focus
RCDs / RCBOs	Indirect contact and leakage current	Rated residual current, device type, selectivity and additional protection in high-risk areas.	User test button, instrument test of trip time/current, nuisance-trip analysis and replacement of non-operating units.
SPDs	Transient overvoltage and lightning-related stress	Coordination by installation zone, earthing, short leads and backup protection.	Indicator status, remote signalling, end-of-life replacement and inspection after severe storms or switching events.
Earthing, bonding and insulation monitoring	Touch voltage and first-fault development	Low impedance protective path and early detection in IT or critical circuits.	Continuity, earth resistance, insulation resistance, alarm checks and trend review.
AFDDs / AFCIs	Series or parallel arcing and ignition risk	Additional fire protection for selected final circuits after risk assessment.	Built-in test, status indication, nuisance-trip review and investigation of loose or damaged conductors.
Temperature and condition monitoring	Hot spots and connection deterioration	Thermal sensors, infrared inspection or smart switchgear in critical boards.	Trend temperatures, tighten verified terminals, correct overloads and document corrective actions.
Cabinet fire suppression	Incipient fire inside electrical enclosures	Pre-engineered aerosol, clean-agent or inert-gas systems for enclosed switchboards.	Inspect indicators, detection circuit, agent condition, enclosure integrity and statutory fire-system records.

3. APPLICATION AS AN OCCUPATIONAL SAFETY MEASURE

From the occupational safety perspective, protective devices should be treated as barriers within a hierarchy of controls. Engineering controls such as automatic disconnection, current limitation, insulation, guarding, grounding and protective devices reduce the probability that a single fault becomes a worker injury [19]. Administrative controls then ensure that work is planned, energized work is avoided unless justified, and isolation, lockout/tagout and verification of absence of voltage are performed before maintenance. Personal protective equipment remains necessary for residual risk, especially for switching or troubleshooting tasks where arc-flash exposure cannot be fully eliminated.

Correct application begins with design verification. The prospective fault current must be known so that the interrupting capacity of protective devices is adequate. Protective conductors, bonding conductors and earthing electrodes must enable disconnection within the required time. RCDs must be selected according to the load and residual current waveform. SPDs must be coordinated with the lightning protection concept and with sensitive electronic equipment. In machinery and production lines, the protective concept also includes emergency stop functions, safe isolation and control-circuit protection [13].

The human factor is equally important. A protective device that trips frequently without diagnosis may be bypassed, replaced with an oversized device, or reset repeatedly without fault finding. These actions convert a design barrier into a latent failure. Workers should therefore understand what each device is intended to protect, which alarms or indicators require action, and why only competent persons may replace or adjust protective devices.

4. PREVENTIVE MAINTENANCE AND TESTING

Preventive maintenance is the structured process by which the protective function is preserved after commissioning. IEC 60364-6 places verification at the centre of electrical safety: inspection is combined with tests such as continuity of protective conductors, insulation resistance, polarity, fault-loop impedance, RCD operating time and functional checks [5]. HSE guidance similarly emphasises that installations and equipment must be maintained to prevent danger, with frequency depending on the equipment, environment and previous inspection results [2, 10].

A practical maintenance programme should combine four evidence streams. First, visual inspection identifies missing covers, damaged cables, overheating marks, moisture ingress, incorrect fuse links and poor labelling. Second, electrical testing confirms that the fault path, insulation and automatic disconnection conditions still meet the design assumptions. Third, functional tests confirm that mechanisms move and indicators operate; this is especially relevant for RCDs, whose test button should be used according to the manufacturer's instructions and whose trip time and current should be verified by a competent person at intervals defined by the installation assessment and applicable requirements [5, 8, 9]. Fourth, records and trends show whether repeated trips, thermal anomalies, insulation-resistance decline or SPD end-of-life indicators point to a developing fault.

Maintenance intervals should be risk based rather than purely calendar based. Harsh environments, vibration, dust, humidity, outdoor use, portable equipment, high load currents and critical production processes justify more frequent inspection and testing. NFPA 70B and ANSI/NETA MTS are North American examples of condition-based maintenance frameworks because they connect maintenance scope to equipment condition, criticality and test evidence [20, 21]. In European installations, they may inform asset-management practice but do not replace IEC requirements, national rules or manufacturer instructions. This risk-based approach supports occupational safety because it focuses effort on the devices whose failure would most directly expose workers to shock, arc, fire or uncontrolled energy.

5. CROATIAN REGULATORY CONTEXT

In Croatia, the application and maintenance of protective devices is connected with both occupational safety and fire-protection regulation. The Occupational Safety and Health Act establishes the employer's duty to organise work and apply preventive measures, while the Ordinance on Safety and Health at Work with Electricity applies to work on, with or near electrical installations, equipment and plants and refers to the Croatian standards series HRN EN 50110 for safe operation of electrical installations [22, 23]. For maintenance practice this means that protective devices must be treated as part of the safe-work system: competent persons, written organisation, work permits where required, and preference for work in a de-energised condition.

The same ordinance explicitly covers inspection, measurement and testing of electrical installations and protective circuits, and it requires the five safety rules for work in a de-energised state: disconnect, secure against reconnection, verify absence of voltage, earth and short-circuit where applicable, and protect against adjacent live parts [22]. It also states that fuse links must not be bridged or replaced with higher-rated links. These provisions directly support preventive maintenance of fuses, circuit breakers, RCDs and other protective devices because they reduce unsafe replacement practices and require competent testing.

Fire-protection regulation is relevant where protective devices are combined with automatic fire detection or extinguishing systems. The Fire Protection Act requires measures to reduce fire occurrence and spread and includes maintenance of fire-detection and fire-extinguishing devices and systems [24]. The Ordinance on Verification of Correctness of Fixed Fire Protection Systems requires initial and periodic testing by authorised legal persons and record keeping for fixed detection and extinguishing systems [18]. Therefore, an automatic extinguishing unit inside an electrical cabinet may be technically useful, but in Croatia it must also be treated as a fire-protection system that requires documented verification when it falls within the regulated system scope.

6. DISCUSSION

The reviewed literature shows that protective devices are effective only as a coordinated system. Overcurrent devices limit thermal and mechanical damage, RCDs reduce the probability of severe electric shock in defined fault scenarios, SPDs reduce overvoltage stress, AFDDs and temperature monitoring improve early fire-risk detection, and earthing and bonding provide the reference path that makes automatic disconnection possible. None of these functions is independent of installation quality, environmental stress or worker behaviour. A technically correct device can still fail as a safety measure if it is inaccessible, poorly labelled, not tested, incorrectly reset, or maintained without isolation.

For small and medium workplaces, the main improvement opportunity is often not a new device but a better maintenance loop: accurate single-line diagrams, labelled distribution boards, planned RCD tests, documented test instruments, timely correction of defects and clear criteria for replacement. For more complex installations, the same principle extends to selectivity studies, arc-flash studies, thermal imaging, AFDD deployment in selected circuits, cabinet fire suppression where justified, breaker testing, power-quality review and post-event inspection after lightning or short-circuit incidents. Such measures support both worker protection and reliability of electrical systems.

7. CONCLUSION

Protective devices in electrical installations are essential preventive measures for occupational safety. Fuses, circuit breakers, RCDs, RCBOs, SPDs, AFDDs, temperature monitoring, cabinet fire suppression and related earthing or monitoring functions reduce the risk of electric shock, burns, fire, equipment damage and uncontrolled energy release. Their contribution is strongest when they are selected according to the installation design, coordinated with other protective measures, Croatian regulatory duties, clear documentation and regular maintenance. Preventive maintenance should therefore be viewed not as an administrative formality, but as the process that keeps the protective function available when a fault occurs. Regular inspection, functional testing, electrical verification and corrective action provide a direct link between technical reliability and worker safety.

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Professional paper

PSYCHOPHYSICAL EFFECTS AND ERGONOMIC RISKS OF LOW–FREQUENCY FLICKER IN LED LIGHTING

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Abstract: *Artificial lighting flicker represents a significant yet often overlooked psychophysical stressor in workplace environments. In this scientific study, the flicker frequency of overhead LED lighting above a cashier's workstation in a retail setting was analyzed. A high-speed digital video recording was examined using a frame-by-frame method, revealing a dominant flicker frequency of approximately 3.6 Hz, which constitutes low-frequency and highly perceptible flicker. This frequency range is known to induce visual fatigue, reduced concentration, irritation, headaches, and, in sensitive individuals, neurological responses. The scientific findings indicate that prolonged worker exposure to such visual stimuli may pose both ergonomic and psychophysical risks, particularly in occupations requiring continuous visual attention and direct interaction with customers. Comparison with relevant ergonomic and safety standards (IEEE) shows that this level of flicker exceeds the threshold of visual comfort and may adversely affect employee well-being and work performance.*

Keywords: *Workplace ergonomics, LED lighting flicker, visual stress, psychophysical effects*

1. INTRODUCTION

Stability of artificial lighting is one of the fundamental prerequisites for visual ergonomics in modern workplace environments. Although LED technology is often promoted as energy efficient and photometrically stable, numerous studies and technical standards indicate that LED light sources may exhibit significant temporal modulation of luminous flux when the power supply is unstable, degraded, or inadequately designed [1,2,3]. Temporal light modulation (TLM) encompasses all forms of periodic variations in light intensity, including visible flicker and invisible modulation components that may exert biological effects [2]. In an ergonomic context, visible low frequency flicker represents the most critical challenge, as it falls within the frequency range to which the human visual system is most sensitive and most reactive.

The human visual system is evolutionarily adapted to detecting abrupt changes in luminance, as such stimuli historically signaled potential threats in the environment. Consequently, low frequency flicker particularly within the 3 to 10 Hz range activates neural mechanisms that increase alertness, tension, and visual load [4,5,6]. According to IEEE Standard 1789–2015, this frequency band is considered the most critical, as it may induce visual discomfort, headaches, reduced cognitive performance, and, in sensitive individuals, neurological responses [1]. Beyond subjective symptoms, flicker can also affect objective measures of work performance, including the speed of visual information processing, precision of motor tasks, and the ability to maintain sustained attention during prolonged work.

In workplace environments with high demands for visual attention, such as retail checkout stations, lighting stability has direct ergonomic and safety relevance. Any deviation from a stable luminous output can increase visual strain, reduce work efficiency, and contribute to cumulative psychophysical stress throughout the workday. Under such conditions, low frequency flicker represents not only a technical lighting issue but also a meaningful ergonomic risk that may affect worker well being.

2. TEMPORAL LIGHT MODULATION (TLM)

Temporal light modulation (TLM) encompasses all forms of periodic variations in light intensity, regardless of their perceptibility. CIE TN 006:2016 defines TLM as any time varying fluctuation of luminous flux, including flicker, stroboscopic effects, and invisible oscillations that may have biological impacts [2]. In LED lighting, TLM is particularly important because LED light sources respond instantaneously to changes in current, meaning that power supply instabilities directly manifest as variations in luminous output. Unlike incandescent lamps, where the thermal inertia of the filament attenuates oscillations, LED technology lacks physical damping, which increases sensitivity to power quality issues and the stability of electronic circuits.

Flicker most commonly occurs due to degradation of electrolytic capacitors in LED drivers, inadequate mains voltage filtering, unstable electrical connections, incompatible dimmers, or component overheating. Since LED diodes themselves do not flicker, the cause is always electronic in nature, enabling precise diagnostics and quantification of temporal modulation. This distinguishes LED systems from traditional light sources, where part of the modulation is suppressed due to slow thermal response.

Temporal modulation of light is described using photometric parameters: a) frequency (Hz) – the number of flicker cycles per second; critical for perceptibility and neurophysiological effects, b) amplitude (modulation depth) – the difference between minimum and maximum luminous flux; higher amplitude increases visual discomfort, c) percent flicker – the relative amplitude expressed as a percentage; enables comparison between light sources, d) flicker index – an integral measure of waveform asymmetry that incorporates the shape of the modulation.

IEC TR 61547-1 further defines Pst (*short–term flicker*) and SVM (*stroboscopic visibility measure*), which quantify short term and stroboscopic flicker effects under real world conditions [3]. Pst refers to flicker perception over a 10 minute interval, while SVM evaluates the visibility of stroboscopic effects during rapid object motion in illuminated spaces, which is particularly relevant in industrial and occupational environments.

In the context of spectral light control, two fundamental phase modulation mechanisms are illustrated in Figure 1. Linear phase modulation (a), known as spectral shearing, induces a Doppler-like frequency shift of the photon packet, whereas quadratic phase modulation (b) acts as a temporal lens that compresses or stretches the optical pulse. These processes arise from the spatiotemporal duality between optical beam diffraction and ultrafast pulse dispersion, and their efficiency depends on modulator parameters, including half wave voltage and operating frequency [7].

For high frequency modulation of LED diodes with minimal waveform distortion, a control circuit is used to reduce the voltage difference between the ON and OFF states. The OFF voltage is set close to the ON state, with the lowest luminous output absorbed by the housing and diffuser. This shortens the LED rise and fall times and preserves the square wave shape. Figure 2 shows measurements of luminous output at four different frequencies; red points represent raw measurements, while black markers indicate their averages [8].

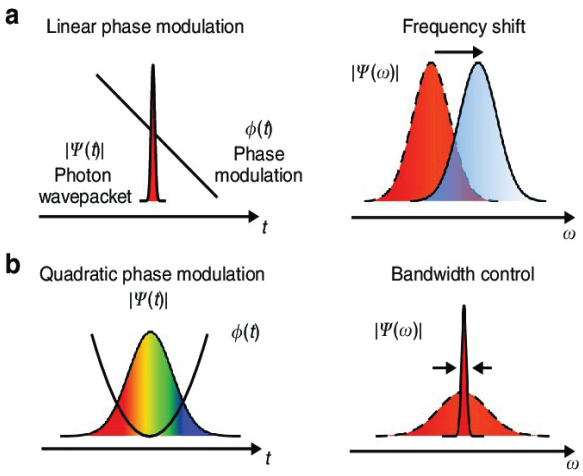


Figure 1: Frequency and Bandwidth Control of Light via Temporal Phase Modulation

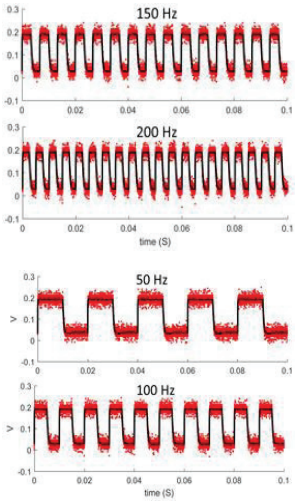


Figure 2: Measurements of Luminous Output at Four Different Frequencies

3. IMPACT OF TEMPORAL LIGHT MODULATION (TLM) ON HUMAN VISION AND HEALTH

Flicker represents a temporal light artifact that the CIE (*Commission Internationale de l'Éclairage*) defines as the perception of visual instability induced by a light stimulus whose luminance or spectral distribution varies over time. Flicker perception is possible up to approximately 90 Hz, depending on viewing conditions, and is influenced by modulation depth, frequency, and light intensity. The human visual response to temporal changes in luminance is illustrated in the ASSIST recommendation, Figure 3, where the red curve shows peak sensitivity around 15 Hz, while the red and green zones indicate regions of increased and decreased perceptibility [9].

TLM can induce three primary visual effects: flicker, the stroboscopic effect, and the phantom array effect. Flicker is perceptible below approximately 80 Hz, whereas above this threshold temporal variations cannot be consciously resolved. The critical flicker frequency (CFF) depends on luminance, the size of the light source, and observer alertness. Due to PWM (*Pulse-Width Modulation*) control and large modulation depths, LED technology can produce all of these artifacts, including the phantom array effect, which is particularly pronounced during rapid eye movements [10,11].

According to IEEE Std 1789–2015, the frequency range of 3 to 10 Hz is considered the most critical for the human visual system because it lies within the band where the brain most readily detects rhythmic luminance changes [1]. In this region, increased neural activation occurs in the visual cortex, which may result in visual discomfort, headaches, reduced concentration, and elevated psychophysiological load [4,5]. The neurophysiological effects of flicker have been extensively documented in the works of Wilkins [4], Bullough [5], and Kelly [6], who were among the first to quantify visual responses to temporally varying stimuli.

Application of exogenous 40 Hz temporally modulated light induces a neural response oscillating at the same frequency as the flickering stimulus, forming the basis of the GENUS concept (*Gamma Entrainment Using Sensory Stimuli*). Visual 40 Hz stimulation can be achieved through luminance flicker (LF), chromatic flicker (CF), or a combination of both. LF and CF elicit the strongest cortical responses but are also the most uncomfortable, whereas CF can induce a neural response with minimal flicker perception, making it suitable for applications where comfort is essential. Invisible Spectral Flicker (ISF) further reduces flicker perception by alternating between two phases of white light with similar correlated color temperatures but different spectra, and can induce a robust 40 Hz response. ISF produces a weaker response than LF but is subjectively rated as significantly more comfortable.

Figure 4 presents a graphical depiction of the neural response of participants at the Technical University of Denmark (DTU) during 40 Hz visual stimulation, confirming that different forms of flicker induce different levels of 40 Hz entrainment and varying degrees of subjective discomfort. The results demonstrate a clear relationship between 40 Hz entrainment strength and perceived discomfort; LF and CF produce the strongest 40 Hz responses but are also perceived as the most flickering and uncomfortable, whereas ISF exhibits the lowest entrainment power and the lowest levels of perceived flicker and visual discomfort [12].

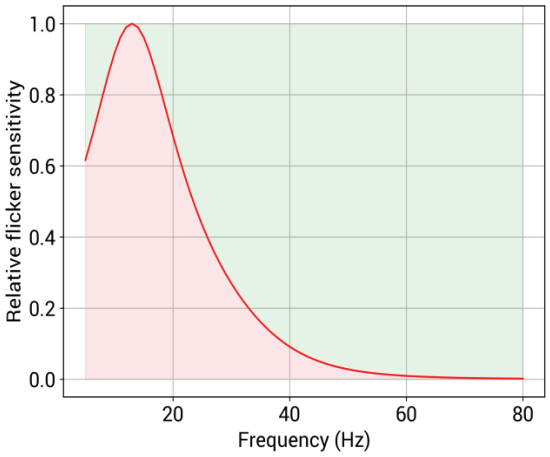


Figure 3: Graphical Representation of Human Visual Sensitivity to Flicker

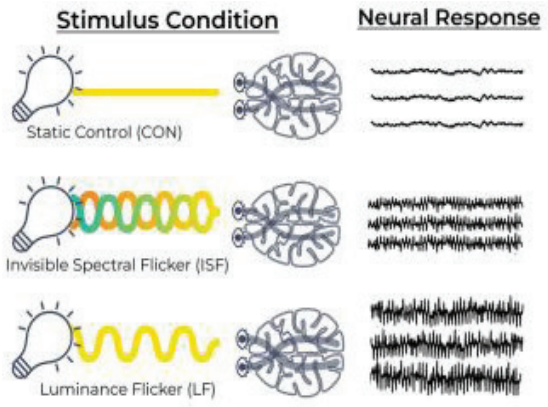


Figure 4: Neural Visual Stress in Correlation with the Level of Perceived Flicker

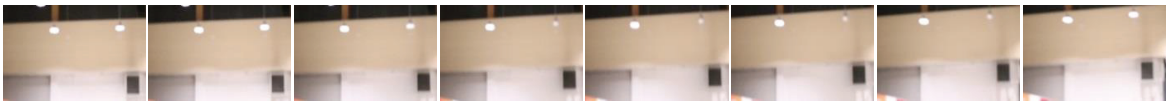
4. EXPERIMENTAL STUDY – ANALYSIS OF LOW FREQUENCY FLICKER IN LED LIGHTING

The experimental measurement was conducted through scientific analysis of a video recording of LED lighting captured with a modern high speed Canon digital camera operating at 100 frames per second (*fps*). High frequency recording enables precise detection of temporal variations in light intensity, particularly in cases of low frequency flicker that is visible to the human eye but requires detailed frame-by-frame analysis for accurate determination of frequency and amplitude.

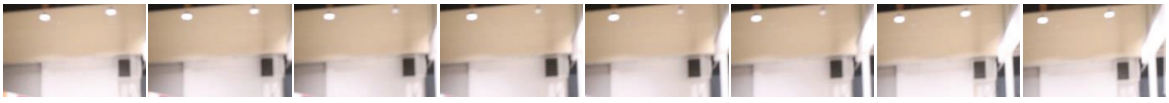
A segment of the video between the timecodes 00:00:58:2560 and 00:01:05:0100 was selected for analysis. The video processing software Adobe Premiere Pro, with the scientifically relevant option Show Audio Time Units enabled, displays time in the HH:MM:SS:UUUU format, where the final segment represents the number of audio units (*samples*). Premiere uses an audio timebase of 48 kHz, meaning that one second contains 48.000 audio units. This method of temporal representation provides significantly finer resolution than standard frame based display, which is crucial for precise measurement of flicker periods.

The difference between the initial and final timecodes is 7.44875 s, which, when interpreted at 100 fps, corresponds to approximately 745 frames. This ensures a sufficiently long sample for reliable analysis of flicker periodicity and stability. Frame-by-frame analysis showed that maximum luminous values recur at intervals of 7 frames at the standard 25 fps, or 28 frames at 100 fps. From this, the period is derived as T = 0.28 s and the flicker frequency as f = 3.57 Hz, rounded to f ≈ 3.6 Hz, which aligns with the visually observed flicker rhythm.

Figure 5 presents the luminous state of each frame within the selected segment. It includes frames from a) to p), corresponding to 00:00:00:0007 to 00:00:00:0022, and shows moments of maximum brightness, phases of brightness reduction, and moments of complete light extinction. A clear cyclic pattern is visible: two frame positions of maximum brightness, followed by a dimming phase, four frames of complete darkness, and then a sudden re-illumination. This pattern repeats at regular intervals, confirming stable low frequency flicker with a very large amplitude (complete light extinction).



a) 0007 MB b) 0008 MB c) 0009 DP d) 0010 CD e) 0011 CD f) 0012 CD g) 0013 CD h) 0014 MB



i) 0015 MB j) 0016 DP k) 0017 CD l) 0018 CD m) 0019 CD n) 0020 CD o) 0021 MB p) 0022 MB

Figure 5: Cyclic Pattern of Stable Low-Frequency Flicker with Complete Light Extinction

YC Waveform analysis, shown in Figure 6, displays luminance (luma) as a time based graph. Each rise and fall cycle of luminance represents one flicker cycle. In this experimental study, the YC Waveform revealed exceptionally clear and deep amplitudes, with luminance dropping to nearly zero during part of the cycle, confirming full light modulation. RGB Parade analysis, shown in Figure 7, demonstrates that the variations occur primarily in the luminance channel, while the RGB components remain stable. This is consistent with luminance flicker (LF), where overall brightness changes rather than color.

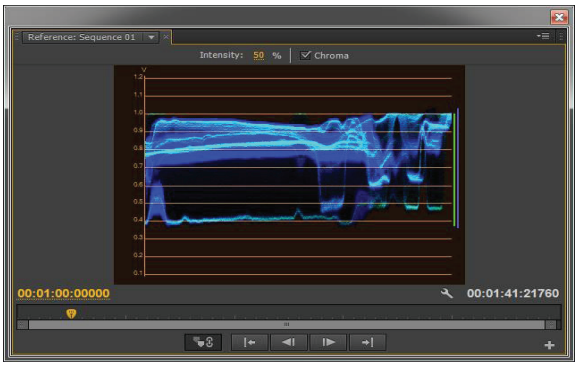


Figure 6: YC Waveform

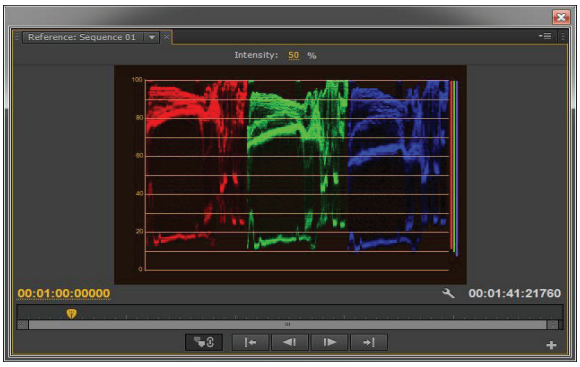


Figure 7: RGB Parade

5. RESULTS AND DISCUSSION

The results of the scientific investigation clearly show that the LED lighting above the cashier's workstation in the retail shopping center generates low frequency flicker at approximately 3.6 Hz, with an exceptionally large amplitude that results in complete light extinction during part of the cycle. This frequency lies within the range most critical for the human visual system, as IEEE Standard 1789-2015 defines the 3 to 10 Hz band as the most sensitive for perceiving temporal light modulation. At the same time, the flicker amplitude in the analyzed case far exceeds all recommended limits, since the IEEE standard recommends modulation below 8 %, whereas nearly 100 % modulation is observed here (the light fully extinguishes during part of the cycle). Such a level of TLM represents the most unfavorable form of flicker, especially in work environments requiring continuous visual attention.

Temporal light modulation (TLM) is defined as rhythmic variation in light intensity, while unwanted visual, cognitive, and physiological effects are considered responses to TLM. Modern LED systems, comprising the LED source, driver, and control electronics, can generate a wide range of luminous waveforms, including very large modulation depths. As a result, they are particularly prone to phantom array effects, stroboscopic effects, and low frequency flicker [10,11]. Low frequency flicker from 1 to 10 Hz is the most visible and irritating because the human visual system readily detects rhythmic changes in brightness. In this range, increased neural activation occurs in the visual cortex, which may result in visual discomfort, headaches, reduced concentration, irritability, and elevated psychophysiological load [1]. Wilkins (2017) notes that flicker in this range can reduce cognitive performance, while Bullough (2012) emphasizes that such frequencies cause discomfort in most individuals. Kelly (1961) was among the first to quantify visual responses to temporally dependent stimuli, confirming that low frequency flicker induces strong neural activation [4,5,6].

Scientific analysis of the video recording showed that flicker cycles repeat at regular intervals of 7 frames at 25 fps, or 28 frames at 100 fps, confirming a stable electronic cause. The YC Waveform display revealed deep luminance amplitudes, with light dropping to nearly zero during part of the cycle. RGB Parade analysis confirmed that the variations occur primarily in the luminance channel, while chromatic components remain stable, consistent with luminance flicker (LF). LED diodes themselves do not flicker; they respond instantaneously. Flicker arises from power instability in the LED driver. The most common causes include capacitor degradation, poor electrical contact, overheating, incompatible dimmers, or low quality electronics. Since each LED lamp has its own driver, failure of a single lamp can cause flicker only at that location, while others operate normally.

The stable flicker rhythm without chaotic interruptions confirms that the cause is a local driver failure rather than a systemic power supply issue.

In the context of the cashier's workstation, exposure to flicker for 7.5 hours per day represents a significant ergonomic risk, particularly because the job requires continuous visual attention, precision, and constant monitoring of visual information. Such conditions amplify the negative effects of flicker, manifesting as visual stress, headaches, reduced concentration, slower task performance, increased error rates, and overall decline in work efficiency. Sensitive individuals may experience dizziness, nausea, and increased risk of photosensitive reactions. The combination of low frequency flicker in the 3 to 4 Hz range, extremely large amplitude involving complete light extinction, prolonged worker exposure, and visually demanding work tasks represents the most unfavorable scenario in ergonomics and neurophysiology. Under such conditions, cumulative psychophysiological load develops, significantly impairing worker well being, which according to all relevant standards constitutes a non ergonomic, health risking, and technically unacceptable form of temporal light modulation requiring immediate intervention.

EEE Standard 1789 specifically emphasizes that frequencies in the 3 to 10 Hz range can affect objective parameters of visual performance, including information processing speed and accuracy of visuomotor tasks, further confirming the importance of flicker control in work environments. Even relatively small luminance fluctuations within this band can accumulate into measurable visual strain, reducing perceptual stability and increasing the cognitive effort required to maintain task accuracy. With prolonged exposure, these effects can subtly degrade visuomotor precision and elevate overall mental fatigue, particularly in occupations requiring continuous visual engagement. This makes consistent flicker mitigation essential for maintaining reliable, long term visual and cognitive performance. The scientific findings of this study highlight the need for systematic monitoring of temporal light modulation in workplaces, regular maintenance of lighting systems, and integration of visual ergonomics into risk assessments. In workspaces with prolonged light exposure, it is essential to use flicker free LED lighting in accordance with IEEE Std. 1789 and modern ergonomic guidelines.

6. CONCLUSION

The experimental analysis of the faulty LED lighting above the cashier's workstation in the retail shopping center revealed the presence of low frequency flicker at ≈ 3.6 Hz, accompanied by an exceptionally large amplitude. This form of temporal light modulation lies within the most critical range according to IEEE Standard 1789–2015 and is associated with visual stress, headaches, reduced concentration, and general psychophysiological strain. The obtained results indicate that the cause of the flicker is a local failure of the LED driver, consistent with the stable flicker rhythm and complete luminance drop within the cycle. Since the workstation requires continuous visual attention, prolonged exposure to such flicker represents a significant and undesirable ergonomic risk.

Low frequency flicker in the 3 to 4 Hz range is particularly unfavorable because it falls within the frequency band to which the human visual system is most sensitive. Long term exposure to such stimulation may lead to reduced work performance, increased error rates, visual fatigue, irritability, and an overall decline in worker well being. In the context of occupational safety, this condition represents a clearly identifiable risk that can affect the safety, health, and psychophysiological stability of employees. Workstations such as cashier desks, where continuous visual attention is required, are particularly sensitive to the effects of flicker, further emphasizing the need for preventive action and technical maintenance of lighting systems.

It is recommended to replace the faulty LED luminaire, use LED lighting with flicker free drivers, perform periodic lighting inspections in work environments, and integrate visual ergonomics into risk assessments. Systematic monitoring of temporal light modulation should become an integral part of workplace evaluations, especially in environments where workers spend extended periods and perform visually demanding tasks.

The results of this study highlight the importance of monitoring and managing low frequency flicker in work environments and encourage further research on the impact of temporal light modulation on human health, well being, and work performance. In the context of occupational health and safety, timely detection and elimination of flicker represent a key measure for preserving visual comfort, reducing psychophysiological load, and ensuring optimal working conditions.

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Original scientific paper

INFLUENCE OF ANTHROPOMETRIC ERRORS ON THE WORKLOAD ASSESSMENT BY THE "RULA" METHOD USING A COMPUTER AND INERTIAL MOVEMENT SENSORS

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Abstract: *The subject of this paper is the research of the influence of errors or deviations from the actual anthropometric dimensions of the measured person during motion recording using an inertial measurement units (IMU) system on the results of computer-based workload assessment using the RULA method. A motion capture system (mocap) based on NOITOM PN3 sensors and Axis Studio software was used, as well as HRV NAWO Live workload assessment software. The hypothesis is that there will be a certain deviation from the actual workload. Given that this measurement method is based on bending angles and joint rotations, it was assumed that it would not be significant. Four cases were analyzed: exact measurement, approximate anthropometric template, template for 15 cm lower height, and template for 15 cm higher height. Key indicators for the same work scenario were analyzed in all four cases. The results indicate a trend of smaller errors.*

Keywords: *ergonomics, RULA method, computer support, inertial sensors, assessment errors*

1. INTRODUCTION

The development of wearable motion measurement systems has enabled the application of digital tools in ergonomic assessment of workload. One of the frequently used methods for assessing upper-body postural load is RULA (Rapid Upper Limb Assessment), developed to rapidly assess the risk of musculoskeletal disorders associated with the positions of the neck, trunk, and upper limbs. The method scores the positions of the upper arm, forearm, wrist, neck, trunk, and legs, while additionally considering muscle activity and external load, and provides an overall score and the corresponding level of required intervention [1].

In this paper, the RULA assessment is performed by recording a work task using the Perception Neuron 3 (PN3) system, processing the movement in Axis Studio, and conducting the ergonomic

analysis in NAWO Live. PN3 is an inertial motion measurement system that uses inertial measurement unit (IMU) sensors placed on body segments. An IMU sensor does not directly measure a joint's position in space. Instead, it measures physical quantities from which its orientation is estimated: the accelerometer measures linear acceleration and the gravity component; the gyroscope measures angular velocity; and the magnetometer can assist in determining orientation relative to the Earth's magnetic field. Since each of these signals has limitations, sensor data fusion is used in processing, i.e., the algorithmic integration of measurements to obtain a more stable estimate of the sensor's orientation and the corresponding body segment's orientation [2].

After calibration, Axis Studio assigns the sensors to body segments and reconstructs the movement of a digital character, i.e., a mannequin. The reconstruction is based on a kinematic model of the body: the known orientation of a segment is combined with its length, and the position of the distal joint is calculated from the position of the proximal joint, the rotation of the segment, and the segment length. In simplified terms, the relationship is: $p_distal = p_proximal + R \cdot l$; where R is the segment rotation obtained from IMU data and l is the segment length defined by the anthropometric model. Anthropometric data, therefore, do not serve only for visual adjustment of the mannequin but also determine the lengths of the trunk, upper arm, forearm, and other segments, thereby influencing the calculated coordinates of joints and endpoints, such as the hand [3].

In industrial settings, it is often not possible to measure all workers' anthropometric dimensions in detail before analysis. Due to limited time and practical constraints, the nearest available male or female height templates in Axis Studio are often used. Such an approximation may be acceptable for a rapid assessment, but it can introduce error into the reconstruction of body position. If the selected model is larger than the actual subject, the kinematic model uses longer segments and distal joints are reconstructed farther from the proximal joints in the direction of the segment orientation; if the model is smaller, the segments are shorter, and distal joints are reconstructed closer. The direction of change of an individual global coordinate cannot be determined unambiguously in advance because it depends on the current posture, but it can be expected that models that deviate more from the actual measurements will produce greater positional deviations.

Given the RULA scoring approach, the expected deviations will most often not be continuous but appear as changes in a segment or total score when the reconstructed posture crosses the boundary between RULA categories. Therefore, for a model very close to the actual height of the subject, small or negligible deviations are expected. At the same time, markedly lower or higher templates may lead to changes of approximately 1 point in the total RULA score and, in borderline postures, also to a change in the action level. Some studies describe and validate Perception Neuron systems for kinematic motion measurement [4, 5], as well as fundamental literature on anthropometry and ergonomic work design [3]. However, according to the available literature, no studies were found that directly examine the influence of an incorrectly selected anthropometric template in Axis Studio on RULA results in the NAWO Live environment, which makes this topic relevant for controlled experimental verification.

Several hypotheses were set in the paper to compare the results with respect to changes in the dimensions of the anthropometric model:

- H0: A change in the anthropometric model does not cause a visible descriptive change in the RULA result.
- H1: A change in the anthropometric model causes a visible descriptive change in the RULA result.
- If H1 is confirmed, additional hypotheses related to deviations in the RULA method with respect to the positions of the upper arm and trunk are also defined:

- H1a: There is a visible descriptive difference in the upper arm score.
- H1b: There is a visible descriptive difference in the trunk score.

2. METHODOLOGY

The study used the previously mentioned and described NOITOM Perception Neuron 3 (PN3) motion capture system. It is a wireless system that enables highly reliable whole-body motion recording. It consists of 17 inertial sensors and does not require cameras, markers, or a line of sight. Axis Studio v2.12 software was used to manage the system and reconstruct the digital model. This software enables entry of the subject's anthropometric measurements, sensor initialization and synchronization, signal quality checks, calibration, and performance of standard calibration poses (T, S, and A). The software displays the digital model in real time and serves as the starting point for connection with other ergonomic tools. HRV NAWO Live software was used for the ergonomic assessment; it is a tool intended to assess the risk of musculoskeletal disorders during physical activities. Video recording was performed using a Microsoft LifeCam HD-3000 camera to monitor and navigate the work scenario, enabling the positions and activities to which the obtained kinematic results refer to be clearly determined. The combination of the PN3 system, Axis Studio, and NAWO Live software enabled the collection of kinematic data and their conversion to digital form. The real-time ergonomic parameters displayed served as the basis for analyzing and demonstrating the influence of anthropometric deviations on the results and the evaluation of the RULA method.

The work scenario consisted of repeated individual lifting of ten packages of A4 paper, each weighing 2.5 kg. A total of ten consecutive lifts were performed. The package was lifted from a height of 24 cm, passed through the L5/S1 level at 100 cm, and placed on the upper shelf of a cabinet at 164 cm. The grip was stable and classified as good. The total time for the task was approximately 1:25 minutes. In NAWO Live, the activity lasted less than 1 hour and was defined as repetitive, with 8 repetitions per minute. In Axis Studio, a model was created using the actual anthropometric measurements of the measured person. After the recording with the newly created 178 cm model was completed, the recording was repeated using the nearest standard template, "male180". After that, two more identical work scenarios were repeated using the selected "male165" and "male195" templates, with calibration repeated for each model and the identical work task performed. Thus, three standard templates were included, with deviations of +2 cm and ±15 cm relative to the subject's actual height.

The paper packages are 5 cm thick and are stacked in groups of 5 in two adjacent columns; the shelf base height is 24 cm. They are stacked in the same arrangement on the higher shelf, whose base is 164 cm high. Since, during lifting of the packages from the lower shelf to waist level (100 cm), the lower position height changes from 44 cm to 24 cm, while the upper shelf height (the lifting action from the waist upward) increases from 164 cm to 184 cm, the first, fifth, and tenth work cycles were selected as characteristic cycles for the analysis. Each cycle was divided into two steps: "Lift 1" (lower shelf to waist level) and "Lift 2" (from the waist to the upper shelf). This approach gives a total of six measurement sequences for comparison. Since the RULA method is precise and based on the categorization of angles, it was assumed that the results between models would be very similar, with possible minor deviations caused by the application of individual RULA rules in cases where the change in anthropometry causes a postural angle to cross into another category [1, 3, 4].

Descriptive statistical methods were applied in the analysis, and the results are considered to indicate tendencies or trends in change based on anthropometric deviations, thereby supporting or not supporting the hypotheses. The sample size is too small for inferential statistics. As a compromise, we also acknowledge that simultaneous measurement across all four anthropometric models within a single work scenario is not possible, which introduces additional uncertainty into the procedure.

3. RESULTS

The comparative presentation of anthropometric dimensions is shown in Figure 1. Disproportionality is observed between the actual measurements and the dimensions of the predefined templates.

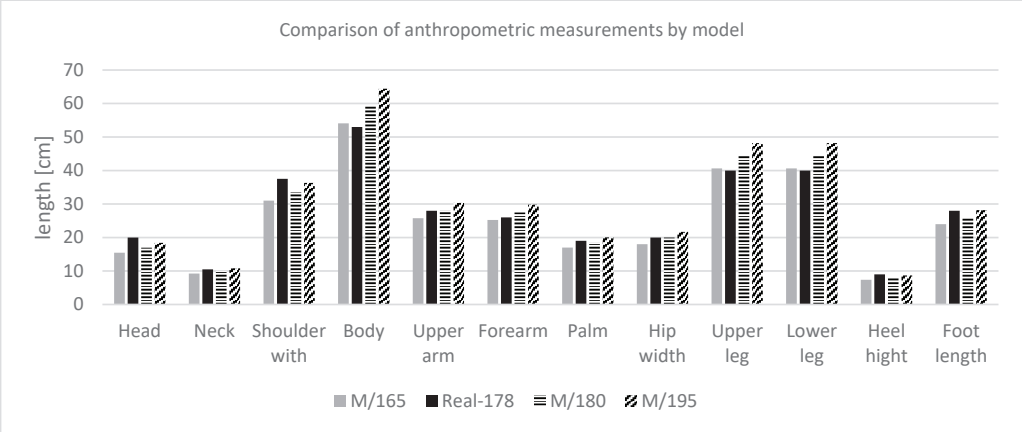


Figure 1: Comparison of anthropometric measurements by model

Since the complete presentation of results would greatly exceed the available space for this paper, the total RULA results are shown in Table 1, while Table 2 shows a differential presentation, i.e., the differences in RULA results by body part for each approximation model (165, 180, 195) and the actual (real) anthropometry (RA). The movement phases from sequence 1, and the Lift 1 step to sequence 3 and the Lift 2 step are labeled D11-D32. It can be observed that, for most upper limb segments, there are no changes in individual or total RULA results; in some cases, the results differ by -1 or +1. Larger deviations of +2 or even +3 are observed for the left hand in 165-RA: D21 (+2), D31 (+3); 180-RA: D21 (+2), D31 (+2); and 195-RA: D21 (+2), D31 (+2). For the right hand, a slightly greater load is observed for 180-RA in D31, amounting to +2. For the left elbow, there are no changes in the results for any of the four models. The movement phases from Lift 1, stabilization of the load at waist height, and Lift 2 are shown in Figure 2. Figure 3 shows the process of workload analysis in the NAWO Live program.



Figure 2: The movement phases

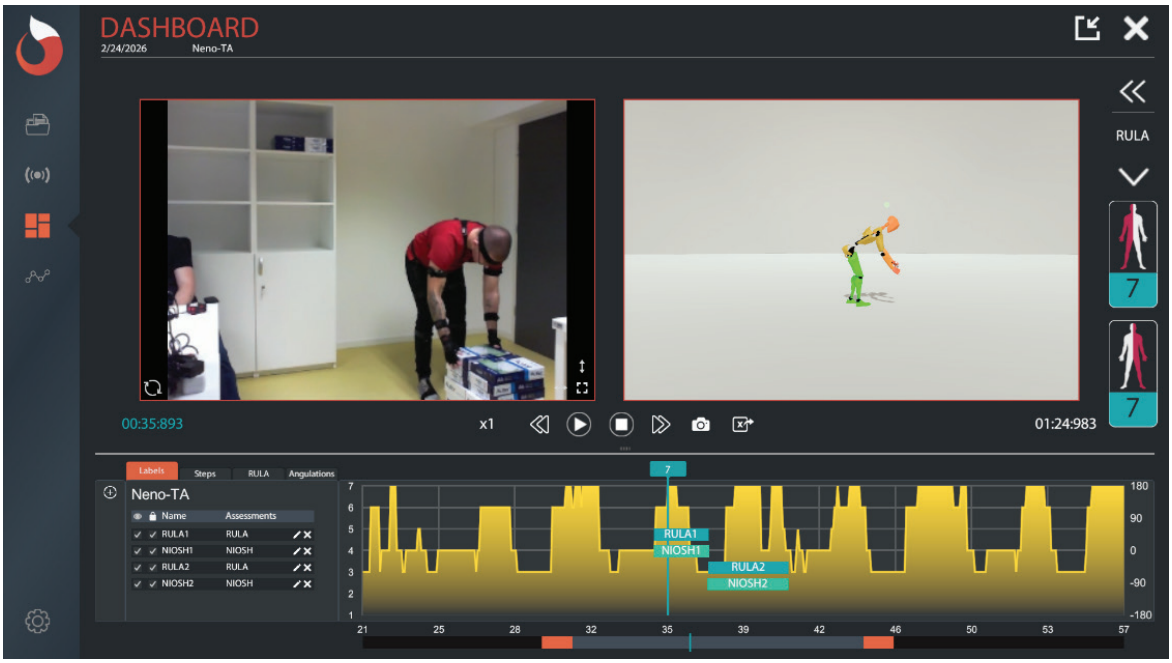


Figure 3: Workload analysis in the NAWO Live program

Table 1: RULA results by movement phases for all four models

Movement phase (165 cm)	Neck	Trunk	Shoulder (L-R)	Elbow (L-R)	Hand (L-R)	Total RULA score
D11	5/6	3/6	2/6 – 3/6	2/3 – 2/3	3/5 – 4/5	6/7
D12	2/6	1/6	3/6 – 3/6	1/3 – 2/3	4/5 – 4/5	4/7
D21	5/6	3/6	3/6 – 3/6	2/3 – 2/3	4/5 – 4/5	6/7
D22	3/6	1/6	2/6 – 2/6	1/3 – 2/3	4/5 – 4/5	4/7
D31	5/6	3/6	2/6 – 3/6	2/3 – 2/3	5/5 – 3/5	6/7
D32	4/6	1/6	3/6 – 2/6	1/3 – 1/3	4/5 – 4/5	5/7

Movement phase (RA - 178 cm)	Neck	Trunk	Shoulder (L-R)	Elbow (L-R)	Hand (L-R)	Total RULA score
D11	4/6	2/6	3/6 – 2/6	2/3 – 2/3	3/5 – 3/5	5/7
D12	2/6	2/6	3/6 – 3/6	1/3 – 1/3	4/5 – 4/5	4/7
D21	4/6	3/6	2/6 – 2/6	2/3 – 2/3	2/5 – 3/5	5/7
D22	4/6	1/6	3/6 – 3/6	1/3 – 2/3	4/5 – 3/5	5/7
D31	5/6	3/6	2/6 – 2/6	2/3 – 2/3	2/5 – 2/5	5/7
D32	5/6	1/6	3/6 – 3/6	1/3 – 1/3	3/5 – 3/5	6/7

Movement phase (180 cm)	Neck	Trunk	Shoulder (L-R)	Elbow (L-R)	Hand (L-R)	Total RULA score
D11	4/6	3/6	3/6 – 2/6	2/3 – 2/3	4/5 – 4/5	6/7
D12	2/6	1/6	3/6 – 3/6	1/3 – 2/3	3/5 – 4/5	3/7
D21	4/6	3/6	2/6 – 2/6	2/3 – 2/3	4/5 – 4/5	6/7
D22	4/6	1/6	3/6 – 3/6	1/3 – 2/3	4/5 – 4/5	5/7
D31	5/6	3/6	2/6 – 3/6	2/3 – 2/3	4/5 – 4/5	6/7
D32	4/6	1/6	3/6 – 3/6	1/3 – 2/3	4/5 – 4/5	5/7

Movement phase (195 cm)	Neck	Trunk	Shoulder (L-R)	Elbow (L-R)	Hand (L-R)	Total RULA score
D11	4/6	3/6	2/6 – 3/6	2/3 – 2/3	3/5 – 3/5	6/7
D12	2/6	1/6	3/6 – 3/6	1/3 – 2/3	4/5 – 4/5	4/7
D21	4/6	3/6	2/6 – 3/6	2/3 – 2/3	4/5 – 3/5	5/7
D22	4/6	1/6	3/6 – 3/6	1/3 – 2/3	4/5 – 4/5	5/7
D31	5/6	3/6	3/6 – 3/6	2/3 – 2/3	4/5 – 3/5	6/7
D32	4/6	1/6	3/6 – 2/6	1/3 – 2/3	4/5 – 4/5	5/7

Table 2: Differences in RULA results by body part for each approximation model

Model	Move. phase	Neck	Trunk	Shoulder L	Shoulder R	Elbow L	Elbow R	Hand L	Hand R	Total RULA score
165-RA	D11	1	1	-1	1	0	0	0	1	1
	D12	0	-1	0	0	0	1	0	0	0
	D21	1	0	1	1	0	0	2	1	1
	D22	-1	0	-1	-1	0	0	0	1	-1
	D31	0	0	0	1	0	0	3	1	1
	D32	-1	0	0	-1	0	0	1	1	-1
180-RA	D11	0	1	0	0	0	0	1	1	1
	D12	0	-1	0	0	0	1	-1	0	-1
	D21	0	0	0	0	0	0	2	1	1
	D22	0	0	0	0	0	0	0	1	0
	D31	0	0	0	1	0	0	2	2	1
	D32	-1	0	0	0	0	1	1	1	-1
195-RA	D11	0	1	-1	1	0	0	0	0	1
	D12	0	-1	0	0	0	1	0	0	0
	D21	0	0	0	1	0	0	2	0	0
	D22	0	0	0	0	0	0	0	1	0
	D31	0	0	1	1	0	0	2	1	1
	D32	-1	0	0	-1	0	1	1	1	-1

4. DISCUSSION

Descriptive statistics were presented for the results, providing an indicative approach. Two elementary sequences were analyzed (lower shelf to waist height, and waist height to upper shelf), which together form the complete lifting sequence (lower shelf to upper shelf). In order to average the results, three complete load-lifting sequences were selected according to the principle of the first, middle, and final sequence (ten packages of paper are lifted, during which the height of the lower shelf decreases and the height of the upper shelf increases), and this work scenario was repeated for four anthropometric models. Inferential statistics would allow confirming the stated hypotheses more reliably in general. However, this would require a significantly larger number of analyzed elementary sequences and, above all, the work sequences for all four anthropometric models would have to be performed equally, i.e., with "robotic" precision. A compromise or uncertainty therefore remains as a consequence of the need to repeat the scenario for each model, because

it is impossible to measure all four anthropometric models simultaneously. Therefore, under these conditions in which distributions of results for related cases are compared, the Friedman test for repeated measurements could be applied separately for Lift 1 and Lift 2, and the application of post hoc Wilcoxon tests could show whether the results for the three approximation models differ statistically significantly from the reference model [6]. Based on the presented descriptive statistics, it can be concluded, as an indication, that the deviation results by body segment are mostly within ±1, confirming that changes in anthropometry do not cause significant changes in biomechanical load nor lead to a change in the overall risk category.

The analysis and comparison of the results show that the total RULA score across all models remains within a narrow range, without changing the overall risk level or entering the high-risk zone. Although differences between the models were observed, especially during movement phases, they are not sufficiently pronounced to be considered a significant trend of change. They also do not affect the final RULA score. Accordingly, the basic hypothesis H0 is accepted, while the alternative hypothesis H1 is rejected. In addition to the main hypothesis, several hypotheses were formulated to provide a more detailed examination of the problem. The analysis of the additional hypotheses showed that although the shoulder (upper arm) score exhibits the greatest variability across models, the values remain within the same scoring range and no significant change in load level occurs. Therefore, H1a is not supported. Similarly, the trunk score shows marked stability, with almost identical values across all models and no significant deviations. H1b is also rejected.

Anthropometric differences did not lead to greater changes in the RULA result; however, they nevertheless affect the distribution of load between body segments and the strategy used to perform work tasks. Judging by this, anthropometry acts indirectly, through adaptation of movement. At the same time, it does not change the final analysis of postural risks.

5. CONCLUSION

Since predefined anthropometric templates rather than actual worker measurements are often used in industrial practice, the paper aimed to determine the extent to which such deviations can affect biomechanical analysis and the final risk assessment. For this purpose, the results obtained for four anthropometric models in an identical work task were compared, with an analysis of how differences in body height and proportions affect load distribution and the RULA result. The study thus provided insight into the reliability of the RULA method under conditions where anthropometry is not fully precise, which represents an important contribution to ergonomic practice and the application of mocap technology in real work environments.

The results indicate that anthropometric differences do not significantly affect the final RULA score. All models, regardless of height, show a medium to high postural risk, without crossing into the high-risk category. The basic level of load in the given work task does not change significantly with changes in anthropometry; rather, it is determined by the nature of the task. This includes repetitive lifting and placing of loads. The greatest loads are visible in the lifting phases, confirming across all models that this part of the task is the most demanding for the worker.

The research concludes that the RULA method is reliable and effective even when anthropometric data differ across models. This is an important finding for industrial practice, where, due to limited available time, predefined anthropometric templates are most often used rather than workers' actual measurements. Although anthropometry can affect the way movement is performed and

the distribution of load, it does not substantially change the overall risk assessment. However, the results clearly show that, for example, an unadjusted work surface height can increase the load on the shoulders and neck, emphasizing the importance of ergonomic workplace design.

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Professional paper

TECHNOLOGICAL DEVELOPMENT OF PROTECTIVE APRONS IN RADIOLOGICAL PROTECTION: THE RELATIONSHIP BETWEEN PROTECTIVE EFFICIENCY AND ERGONOMIC REQUIREMENTS

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***Abstract**: The development of protective aprons in radiological protection is the result of continuous technological advancement and the need for effective worker protection. Traditional lead aprons provide a high level of protection due to the properties of the material; however, their weight and construction can represent a significant ergonomic burden during prolonged use, which is particularly important in the field of occupational safety and health.The aim of this paper is to present the technological development of protective aprons, with an emphasis on the comparison of different models and materials, including one-piece and two-piece models, lead and composite materials with a reduced lead content, as well as lead-free materials. Through a literature analysis, the types of aprons, the level of protection, and new solutions that reduce physical strain while ensuring the required radiological protection will be presented. Despite the application of technical and organizational measures, properly selected personal protective equipment in radiological protection remains a key element in the management of occupational risks.*

***Keywords:** protective aprons 1, radiological protection 2, lead and composite materials 3, ergonomics 4, personal protective equipment 5.*

1. INTRODUCTION

Ionizing radiation, discovered at the end of the 19th century by Wilhelm Conrad Röntgen, is today indispensable in medicine, industry, and science, particularly in diagnostic radiology and interventional procedures. Despite its significant benefits, early researchers such as Marie Curie

also recognized the potential harmful effects of exposure, which over time led to the development of protective measures [1].

In accordance with the ALARA principle (As Low As Reasonably Achievable), exposure to ionizing radiation is reduced to the lowest possible level through the application of technical and organizational measures, with personal protective equipment representing an important component of the protection system [5]. A special role within this system is held by protective aprons, which are traditionally made of lead. Due to their weight, lead aprons may negatively affect work ergonomics, which in the long term can contribute to the development of musculoskeletal disorders [2], [3], [4].

With the development of new materials, composite and lead-free protective aprons have appeared on the market, which, compared to conventional lead aprons, enable weight reduction while maintaining the required level of radiation protection [5]. All types of aprons must comply with the EN 61331 - *Protective devices against diagnostic medical X-radiation standard,* which prescribes minimum requirements for protection, dimensions, design, and labeling of equipment [6], [7]. In this context, the development of composite and lead-free materials is aimed at improving the ergonomic properties of protective equipment and working comfort, while simultaneously maintaining the required level of radiological protection.

This paper presents lead-based, composite, and lead-free protective aprons, their protective properties, and the potential effects of their use on the user.

2. PROTECTIVE APRONS

Protective aprons represent the primary means of personal protection in radiological practice, and their properties and effectiveness are defined by several key parameters. One of the most important indicators of protection is the material's ability to attenuate radiation. This value is expressed as lead equivalent (mm Pb) and represents a measure of the level of protection—i.e., the extent to which the material attenuates radiation compared to pure lead [8].

A higher lead equivalent provides a higher level of protection; however, it also increases the weight of the apron. In addition to the lead equivalent, the total weight of protective equipment depends on the design of the apron. Accordingly, single-piece models (front protection and wraparound types) and two-piece models (vest and skirt) are distinguished, as shown in Figure 1 [9].

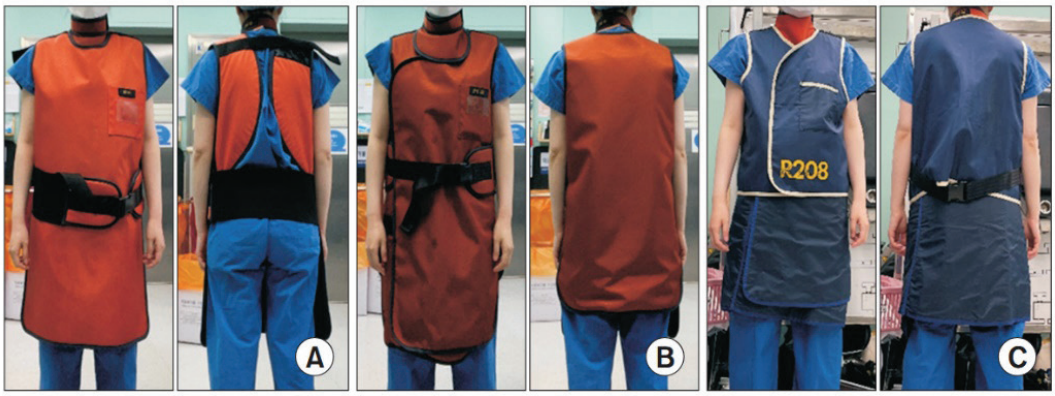


Figure 1: Types of protective aprons: single-piece models (A – front, B – wraparound) and two-piece models (C – vest and skirt) [9].

Single-piece aprons are simpler to use but may cause greater ergonomic strain, whereas two-piece aprons allow for a better distribution of weight between the shoulders and hips. The weight of protective aprons can range from approximately 7 to 15 kg., depending on the protection level and design type, which further emphasizes the importance of ergonomic features in their daily application [2], [4].

2.1. Lead-Based Protective Aprons: Material, Lead Equivalence, and Design

Lead-based protective aprons consist of a polymer matrix in which lead particles are distributed [1], [8]. The polymer materials protect the lead particles from mechanical damage, improve the durability of the apron, and provide flexibility as well as better adaptation to the body.

The protective characteristics of lead aprons primarily depend on the lead equivalence, where a higher equivalence provides a higher level of protection. The efficiency of X-ray attenuation can range from approximately 75% for 0.25 mm Pb to more than 95% for 0.5 mm Pb at standard diagnostic energy levels.

As shown in Figure 2, an uneven distribution of lead within the protective apron is evident, with the highest concentration in the central region, gradually decreasing toward the edges [10]. High-risk areas of the apron, such as the frontal region, contain material with a higher lead equivalence to ensure enhanced protection, while less exposed areas are protected with lower lead-equivalent material, thereby achieving a balance between safety and comfort.

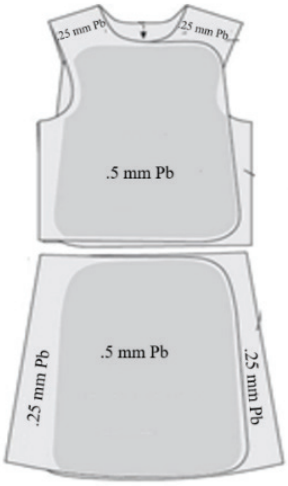


Figure 2: Distribution of lead equivalent thickness (mm Pb) within a protective apron [10]

Protective aprons should have thickness and materials adapted to the actual level of exposure in order to ensure adequate protection. Aprons with a lead equivalent of 0.25 mm Pb are intended for low-energy radiation (<80 kVp), while 0.35 mm Pb equivalent covers medium energies (80–120 kVp), and 0.5 mm Pb provides protection at higher diagnostic energy levels (120–150 kVp).

This range of lead equivalents covers most standard radiological procedures (X-ray examinations, fluoroscopy, and low- to medium-energy CT scans). Radiation energies above this range are not permitted in the immediate vicinity of the operator; in such cases, other protective measures are applied, such as distance, shielding barriers, or working outside the room, thereby ensuring staff safety.

A higher lead equivalent provides better protection but also increases the weight of the apron, which leads to greater musculoskeletal load during prolonged use [2], [11]. It can be stated that there is a trade-off between the level of protection and ergonomics: a higher lead equivalent means better protection, but also a heavier and less comfortable apron.

The design of aprons also affects practical usability: single-piece models are characterized by weight concentration on the shoulders, whereas two-piece models allow for a more even distribution of weight without compromising protective function. Uniform dispersion of lead particles within the polymer layer is essential for reliable and safe protection during use.

In addition to standard models, protective aprons with enhanced local shielding are also available, in which critical areas such as the chest region are reinforced with a thicker layer. Such a design enables increased radiation attenuation in the most exposed organs, while the overall weight of the apron is kept within acceptable limits. Locally reinforced layers are often combined with two-piece systems in order to further distribute weight evenly, reduce spinal load, and improve ergonomics during prolonged use.

2.2. Composite and Lead-Free Protective Aprons: Materials, Lead Equivalence, and Structural Design

New materials began to be introduced in the late 20th century in the development of protective aprons as a response to the need to reduce the weight of lead aprons, which in turn improves ergonomics and reduces both health and environmental risks [5]. Modern models are made of advanced composite and lead-free materials, often with additions of high atomic number metals, which enable the maintenance of a high level of protection against X-ray radiation while simultaneously improving comfort and safety during use in radiological practice.

Composite protective aprons are designed to combine shielding effectiveness with reduced weight and improved ergonomics. These models use a polymer matrix in which particles of high atomic number metals are dispersed—most commonly bismuth (Bi), tungsten (W), antimony (Sb), and occasionally barium (Ba) for lower energy ranges. In addition, a small amount of lead may be present to further enhance attenuation of specific X-ray energy ranges. Such a combination enables optimization, where each element selectively attenuates radiation within a specific energy range, resulting in broad-spectrum protection while reducing overall weight compared to traditional lead aprons [12], [13].

On the other hand, fully lead-free aprons use similar composite structures but without the presence of lead [14], [15]. The focus is on environmental sustainability, safety in production and disposal, while maintaining a high level of protection through the combination of high atomic number metals. The shielding effectiveness of these aprons typically corresponds to a lead equivalence of 0.25 to 0.5 mm Pb, covering most diagnostic energy ranges (X-ray imaging, fluoroscopy, and low- to medium-energy CT scans) [13], [15].

Both types of materials (composite and lead-free) enable a reduction in apron weight by 20–30% compared to conventional lead models, thereby reducing static load on the spine and shoulders and improving ergonomics during prolonged use [13], [14]. Locally reinforced layers provide protection to the most exposed areas, while two-piece designs further distribute weight and reduce biomechanical stress on the user.

2.3. Examples of Commercial Products

A variety of commercial materials are available on the market as alternatives to traditional lead aprons. The most notable include:

- **Xenolite®** – available in low-lead (lead-composite) and fully lead-free versions, flexible and up to 30% lighter than conventional lead aprons; lead equivalence ranges from 0.25 to 0.5 mm Pb.
- **EarthSafe®** – a fully lead-free solution focused on environmental sustainability and ergonomics; a combination of Bi, Sb, and Ba provides reliable protection at standard diagnostic energy levels.
- **Zero™ and Vital™** – lightweight composite materials containing rare earth elements, flexible, with a lead equivalence of up to 0.5 mm Pb; significantly reduce user burden, particularly during prolonged procedures.

These materials represent a new generation of protective equipment that balances maximum radiation protection with minimal user burden, integrating physical safety and ergonomic sustainability in modern radiological practice.

2.3. Advantages and Limitations

Lead aprons have numerous advantages that make them a reliable choice in diagnostic radiology. Primarily, they provide high efficiency in X-ray attenuation, with protection clearly defined by lead equivalence, which enables predictable and reliable protection of personnel. The material and construction of the aprons, including locally reinforced layers, allow targeted protection of critical organs, while the polymer matrix contributes to durability and easy maintenance of the equipment.

On the other hand, conventional lead aprons also have significant disadvantages. Their increased weight, especially at higher lead equivalence levels, can cause spinal and musculoskeletal strain during prolonged use, and ergonomics are limited in single-piece designs. Material rigidity may reduce comfort, while the presence of lead also represents potential health and environmental challenges during production, maintenance, and disposal of the equipment.

Table 1. presents a comparison of the advantages and disadvantages of conventional lead aprons and modern composite and lead-free protective aprons, with emphasis on shielding properties, ergonomics, and practical challenges in use.

Table 1. Comparison of protective aprons

Type of apron	Advantages	Disadvantages
Lead aprons	High X-ray attenuation efficiency	Weight limiting ergonomics
	Targeted organ protection	Musculoskeletal strain
	Durability and easy maintenance	Negative environmental impact of lead – disposal issues
Composite and lead-free aprons	Reduced weight and improved ergonomics	Higher cost
	Flexibility and greater comfort	Possible minor areas of reduced attenuation
	Optimized attenuation according to radiation energy	Requires careful selection of layers and thickness
	Lower environmental impact during disposal	Long-term durability is still under evaluation

3. CONCLUSION

Lead-based protective aprons represent the reference standard in radiological protection due to their high X-ray attenuation efficiency. However, their considerable weight and adverse ergonomic effects may lead to long-term strain on the spine and musculoskeletal system, particularly during prolonged interventional procedures [2], [4], [11].

Lead-free and composite aprons offer improvements in terms of ergonomics, reduced physical load, and comfort; however, they require careful selection of layers and thickness to maintain adequate protection. Two-piece systems further contribute to reducing biomechanical load, but proper use is essential to preserve their shielding effectiveness.

Future development of protective equipment should focus on intelligent, hybrid solutions that integrate optimal radiation protection, reduced weight, and adaptation to individual user needs. In parallel with technological advancement, it is necessary to strengthen awareness of ergonomics and the correct use of protective equipment.

In conclusion, the key objective is not to identify the “best” apron, but to achieve a balance between maximum radiation protection and minimal user burden, thereby ensuring a safer and more sustainable working environment in radiology.

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Professional paper

PROTECTIVE SPORTS EQUIPMENT

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Abstract: *Each sport has prescribed protective equipment that must be worn to prevent potential injuries to athletes themselves. This paper analyzes the importance of the proper use of protective equipment in different sports and presents the most common types of equipment used to prevent injuries during activities. Special attention is paid to material technology and standards that ensure the quality and functionality of sports protective equipment.*

The aim of this paper is to determine how sports protective equipment (for individual, contact and combat sports) affects the risk of injuries among athletes.

Keywords: *protective equipment, sports, injuries*

1. INTRODUCTION

Protective sports equipment plays a key role in injury prevention and athlete safety during training and competition. When engaging in sports activities, whether professional or recreational, there is a risk of injury. Sports often require great mental and physical effort, and in such conditions where fatigue occurs, there is an increased likelihood of injury, both in contact and non-contact sports. Therefore, in parallel with the development of sports, various types of protective sports equipment have been developed.

Throughout history, the development of this equipment has been driven primarily by injury prevention, but also by technological advances that would enable more effective, comfortable, and durable protective sports equipment. From simple improvised equipment throughout history to the sophisticated equipment we have today, protective equipment in sports has maintained a broader social and scientific evolution. The first forms of protective equipment in sports appeared in ancient times, when fighters in Greece and Rome used leather straps and simple helmets to protect the head and body during fights and competitions [1]. During the development of industry and the subsequent

development of materials, the quality and availability of protective sports equipment have significantly affected. With the introduction of plastic, foam, Kevlar fibers, and other lightweight but strong materials in the second half of the 20th century, protective equipment has become significantly more effective and specialized for certain sports. An example is the helmets in American football, which were once made of leather, but are now made of impact-resistant composite materials and lined with an internal protective foam that absorbs impact energy. Similarly, mouthguards, which were once simple and uncomfortable, are now custom-made using 3D scanning and biocompatible materials [1]. In addition, advances in biomechanics and sports medicine have enabled the scientific analysis of injury mechanisms, further improving the design and effectiveness of protective equipment. Today, many professional athletes are equipped with smart equipment that monitors physical parameters, the level of stress on the body, and helps prevent injuries.

With this in mind, the aim of this paper is to highlight the importance of protective equipment in sports, describe the types of protective equipment—including their purpose, methods and areas of application, and proper use—and investigate how such equipment can prevent injuries and positively influence an athlete's psychological state.

2. PROTECTIVE SPORTS EQUIPMENT

Injuries to athletes have always been the main impetus for the development of protective equipment. The occurrence of serious injuries, especially in sports where blows to the head and body, as well as falls, are frequent. Most often, such tragic injuries were the reason for the reaction of sports federations, manufacturers and the scientific community. Research has shown that the long-term consequences of frequent blows to the head can cause chronic neurological diseases. With this knowledge, a greater focus was placed on head protection, where helmets became mandatory in sports that are today unthinkable without them, and over time, helmets with multi-layered structures were developed that better absorb impacts and reduce the risk of concussion [2].

Also, injuries to the joints, knees and lower legs are common in sports such as skiing, basketball and football. Such injuries have led to the development of protectors (bone guards) and various orthoses that help during sports activities, both for the purpose of injury prevention and rehabilitation and a faster return to sports.

Protective sports equipment requires constant adaptation of a person to the demands of the sport and the nature of the injuries. Modern sport is unthinkable without effective and high-quality protective sports equipment, the development of which will continue to follow the needs of athletes and new technological achievements [2].

2.1. Shin guards

In many sports, especially those involving contact or high speeds, such as football, ice hockey, rugby and similar, the wearing of protective equipment, including shin guards, is often mandatory. Their primary function is to reduce the risk of bone fractures and muscle tissue injuries, thus contributing greatly to the safety of athletes. Among the most commonly used protective equipment are shin guards, which are made of durable materials such as plastic, EVA foam and fiberglass [4]. These materials provide high impact resistance, while the inner lining is usually made of soft materials to ensure comfort during wear. The correct size and correct attachment of shin guards are crucial for their effectiveness.

Standards and regulations relating to the manufacture and use of shin guards are strictly defined, with the aim of ensuring their functionality and protective role. In addition to correct use, regular inspection of shin guards throughout the sports season plays an important role in maintaining their effectiveness and safety function.

2.2. Mouthguards

According to numerous scientific studies, more than 50% of all sports injuries involve soft tissues, primarily the lips, while a smaller percentage, around 10%, are jaw fractures and temporomandibular joint injuries. Therefore, sports mouthguards are one of the most important preventive devices, the purpose of which is to reduce the risk of jaw and tooth injuries, as well as to mitigate the consequences if they occur [5].

Dental guards are divided into external and internal. External guards have the role of protecting the jaw, temporomandibular joint and teeth from direct impacts, especially in disciplines characterized by the presence of strong forces directed towards the head and neck, such as combat sports, American football and hockey. Internal dental guards are used in almost all sports disciplines, and with regard to the level of adaptation, they are divided into ready-made, partially adjustable and individually made models. Ready-made mouthguards, although the simplest and most affordable, are also the least comfortable because they are held in the mouth only by the pressure of the teeth, which makes breathing difficult and communication difficult. Partially adjustable shields are made of thermoplastic materials that soften in hot water and thus partially mold to the user's mouth. The highest quality protection is offered by individually made guards, which are shaped according to the precise models of the athlete's jaw. Thanks to their perfect fit, they enable unhindered breathing and speaking and eliminate the need for additional support in the mouth [5].

2.3. Helmet

Helmets are essential protective equipment in sports where there is a risk of head injury. A properly selected and used helmet plays a key role in preventing head injuries in sports [5]. Helmets are mandated or strongly recommended in various sports, such as cycling, skiing, snowboarding, motorcycling, skydiving, hockey, and American football. Helmets are also commonly worn in football, where they are worn by players or goalkeepers after a head injury to prevent re-injury.

Helmets for sports are designed specifically for each sport and generally meet certain requirements or regulations to provide the highest possible level of protection. They are usually made of hard materials such as polycarbonate, fiberglass, or a combination of other materials. They provide protection against head injuries from impacts, falls, or collisions that occur during play or driving [5].

2.4. Nose guard

A nose guard is a piece of sports equipment designed to reduce the risk of nose injuries during sports activities. It is most commonly used in contact sports such as boxing, hockey, rugby and martial arts. Nose guards are also increasingly seen in football where they are used more as a means of preventing re-injury [6].

A nose guard usually consists of a hard plastic or metal material that is placed over the nose and secured to the head or ears with straps. Depending on the sport and the athlete’s preference, guards vary in shape and size. They are designed to absorb or distribute the impact of a blow to the

nose and prevent injuries such as nasal fractures, bleeding or cartilage damage. In addition to their primary function of protection, guards contain soft pads or linings for comfort.

2.5. Neck, shoulder and chest protectors

During sports activities, especially those in which athletes are involved in collisions and falls, protection of the upper body is necessary. Neck, shoulder and chest protectors play this role. Some of the sports in which these protectors are most commonly used are American football, rugby and hockey. Shoulder and chest protectors are placed on the upper body; most of the time they provide support and absorb impact to reduce the risk of injury. They are an integral part of the equipment in American football and hockey, and also appear in certain combat sports where athletes may use these protectors to protect the chest and abdomen [6].

Neck, shoulder and chest protectors are generally made of strong materials such as plastic, Kevlar or composite materials. The correct selection of these protectors by the athletes themselves and the importance of their proper use will lead to a reduced risk of injury.

2.6. Elbow and knee pads

Elbow and knee pads are sports equipment that are used to protect the elbow and knee joints during sports activities, mainly in those sports where there are frequent impacts, falls or excessive loads on the said joints. They are crucial in maintaining safety and preventing injuries.

Elbow pads usually have a hard, anatomically shaped shell that covers the elbow joint. It is intended to absorb the main force of an impact or fall. The inner lining is soft, providing comfort to the athlete using the protector. Elbow pads are widely used in sports including skateboarding, cycling and handball, where the elbow is particularly exposed to falls or impacts. In contrast, knee pads are designed to protect the knee from injury. They also have a hard shell that covers the knee and absorbs the force of the impact [6]. These protectors are commonly used in skateboarding, cycling, rollerblading, skiing and snowboarding.

2.7. Gloves

Gloves are one of the most common types of protective sports equipment. They are used in sports where the hands are exposed to hazards and injuries. In addition to protection, they can also be used for functionality, for example, to provide better grip, improve grip, provide warmth, and reduce friction between the palm and sports equipment. In ice hockey, all players must wear protective gloves. There are differences in design for players and goalies, with field players using smaller and lighter gloves that allow for greater mobility and better stick control. On the other hand, goalies use slightly wider and thicker gloves, due to the fact that they catch the puck with their hands during play. In combat sports, gloves play a key role in protecting the hands and wrists. For example, boxing gloves are designed to absorb shock and reduce the risk of injury, both for the person punching and the opponent. They are much thicker than MMA gloves and cover the entire hand, with the fingers immobile [7]. In mixed martial arts (MMA), gloves allow for greater finger mobility, are thinner than in boxing, but still protect the hands, and are adapted to the specifics and rules of that sport. In soccer, goalkeepers use gloves that improve their ability to catch the ball and provide additional protection for their fingers when defending the goal. These gloves contain reinforcements and special materials that provide a better grip, reduce the possibility of the ball slipping out of the hand when catching, and cushion the impact of the ball. In disciplines where a firm and secure grip is crucial, such as climbing, sports gloves help reduce friction between the hand

and the surface, increase movement control, and reduce the occurrence of the most common injury, which is blisters. Gloves used in cycling allow for better control of the bicycle, reduce vibrations, and protect the hands from possible injuries during falls, as well as from prolonged stress on the hand while riding [7]. In winter sports, such as skiing and snowboarding, gloves are primarily used to provide warmth. Their task is to preserve warmth and protect the hands from cold, frostbite and adverse weather conditions, which allows comfortable and safe performance of sports activities even in extreme conditions. In gyms and during weight training, fitness gloves serve to protect the palms primarily from blisters and scratches and provide a firmer and more secure grip on equipment and dumbbells. In addition to protecting the hands, they also contribute to better movement control and greater exercise efficiency. Baseball gloves allow for precise catching of the ball, golf gloves provide optimal contact with the club without slipping, while diving gloves are used to protect the hands in underwater conditions, providing warmth and protection from sharp surfaces.

The variety of sports gloves reflects the adaptation of equipment to the specific requirements of individual sports, and the correct use and selection of gloves can significantly contribute to the safety, performance and comfort of athletes [7].

2.8. Genital protectors

Genital protectors are protective sports equipment that serve to protect the genitals during training or competition. Their task is to protect the sensitive area from direct impact or collision. They are used in contact sports such as boxing, MMA and hockey (goalkeepers). These protectors are made of very strong materials such as hard polymers or steel that are designed to absorb the force of the impact and prevent serious tissue damage. The outer protective part is most often inserted into an elastic support made of breathable, antibacterial fabrics or into a special pocket that is built into protective shorts. This stabilizes the protector, and friction and discomfort are minimized [7].

Modern models are produced in several sizes and ergonomic profiles to adapt to the body shape and sporting requirements of the individual. Correct size selection and correct placement are key to complete protection and comfort: the protector should fit tightly, but should not restrict movement, interfere with circulation or cause skin irritation.

3.9. Protective Pants

Protective pants are used in numerous sports involving a risk of physical contact, abrasions, falls, or collisions. They are commonly used in hockey, mountaineering, and cycling. In football, handball, and other team sports, protective pants—or jerseys with additional limb protection—are primarily worn by goalkeepers, whereas outfield players wear jerseys designed not for protection but simply to display the club crest and player number [7]. In hockey specifically, protective pants are a crucial component of protective gear. They are constructed from thicker, more durable materials and feature additional padding around the hips, thighs, and lower spine to absorb impacts during play.

While the design and materials of protective pants vary by sport, key features include reinforcements in critical areas (hips, thighs, knees) as well as flexibility and breathability, ensuring unrestricted movement during activity [7]. Well-designed pants must strike a balance between protection and ergonomics, offering maximum safety without hindering mobility.

4. THE IMPACT OF PROTECTIVE EQUIPMENT ON ATHLETE PERFORMANCE

Protective equipment is an indispensable part of training or competition, especially where the risk of injury is higher. However, its impact on athlete performance is not always necessarily positive. On the one hand, it provides safety and reduces the risk of injury, on the other hand, it can bring certain challenges that affect freedom of movement and comfort.

The most important advantage of wearing protective equipment is a significant reduction in the risk of injury. Helmets, guards, protective pants and other equipment protect certain parts of the body from impacts, falls and other hazards that are common in most sports and activities, especially contact ones. This allows athletes to focus on the technique and tactics of the game, keeping in mind that they are well protected [12].

Also, the security provided by protective equipment can have a positive psychological impact. When an athlete feels protected, his sense of security can increase self-confidence and reduce the fear of injury, which contributes to better concentration and a more aggressive approach to competition. Ultimately, reducing injuries prolongs an athlete's career and reduces the time spent away from training due to injury recovery.

Despite its many benefits, protective equipment can also have negative effects on athlete performance. One of the most common problems users experience is the reduction of certain movements. Some types of equipment, especially those that provide heavy protection, can be stiff or uncomfortable to wear and can reduce freedom of movement, which can affect agility, speed, and technique in performing certain actions in sports [12]. The weight of the equipment can also be a problem because it can increase fatigue, reduce endurance, and make it difficult to perform precise and rapid movements. This is especially important in sports where agility and speed are key factors for success, such as hockey or martial arts [12]. Additionally, wearing protective equipment can lead to discomfort, overheating, and reduced breathability, which negatively impacts an athlete's concentration and endurance, especially during long training and competition sessions.

Protective equipment plays a key role in protecting athletes and reducing the risk of injury, which directly contributes to safer and longer-lasting sports participation. It is therefore important to find the optimal balance between protection and freedom of movement, and the development of new materials and technologies is aimed at precisely this – creating lighter, more comfortable, and more efficient equipment that will not compromise athletic performance [12].

5. CONCLUSION

Protective sports equipment is an indispensable part of sports today, whether recreational, amateur or professional. It is not only an accessory for the athlete, but also the key to maintaining health and safety while playing sports. Conducting research and testing new forms of protection and their materials is essential to reduce the number of injuries and permanent consequences to the body during activities. In addition to this role, increased safety gives athletes greater confidence, and can also increase the number of people playing sports. In order to best use these tools, in addition to scientists, an important role is played by sports associations that will implement this knowledge into the rules, and athletes who will use them correctly and regularly.

The development of protective sports equipment is keeping pace with technological advances and following the individual needs of athletes. The future of this equipment promises significant innovations that will further improve the safety, comfort and performance of athletes, with a greater focus on personalization and sustainability [13]. Technology will continue to play a key role in the advancement of protective equipment. The implementation of smart sensors and devices in equipment will enable the monitoring of athletes' vital signs, such as heart rate, body temperature, and biomechanical data on movements and impacts. Further development of advanced materials, such as ultra-light nanomaterials and foams that adapt to the shape of the body, will increase comfort and safety. 3D printing will become the standard in the production of customized equipment, enabling perfect fit and personalized designs that fully meet the individual needs of each athlete [14]. Personalization will become a dominant trend in sports equipment. Not only will equipment adapt to the athlete's body dimensions through 3D scanning and printing, but the design, colors and functionalities will also be able to be individually adjusted [15].

The future of protective sports equipment is also expected to be marked by the integration of sustainable and environmentally friendly materials, in order to reduce the negative impact on the environment. Recyclable and biodegradable materials will be increasingly present in production. Also, with the development of virtual reality, athletes will be able to use equipment that is connected to digital performance analysis systems, which will further improve training and safety [16].

Finally, protective equipment is expected to become increasingly lightweight and ergonomic, with a greater focus on adapting to individual needs and the specificities of sports. This will reduce the negative impacts on mobility and performance and will allow athletes to fully utilize their potential. The future of protective sports equipment lies in the collaboration of advanced technologies, personalization and sustainability. These innovations will not only raise safety standards, but will also allow athletes greater freedom of movement, comfort and monitoring of their health in real time. Thus, the equipment will become not only a shield, but also an important ally in achieving top sports results.

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Original scientific paper

INFLUENCE OF ANTHROPOMETRIC ERRORS ON THE WORKLOAD ASSESSMENT BY THE "NIOSH" METHOD USING A COMPUTER AND INERTIAL MOVEMENT SENSORS

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Abstract: *The subject of this paper is the research of the influence of errors or deviations from the actual anthropometric dimensions of the measured person during motion recording using an inertial measurement unit (IMU) system on the results of computer-based workload assessment using the NIOSH method. A motion capture system (mocap) based on NOITOM PN3 sensors and Axis Studio software was used, along with HRV NAWO Live workload assessment software. The hypothesis is that there will be a certain deviation from the actual workload. Given that this measurement method is based on assessing the workload during lifting, it was assumed that deviations in the reference lifting heights and the distance of the load from the body could result in significant differences in the measured values. Four cases were analyzed: exact measurement, approximate anthropometric template, template for 15 cm lower height, and template for 15 cm higher height. Key indicators for the same work scenario were analyzed in all four cases. The results indicate a trend of larger errors.*

Keywords: *ergonomics, NIOSH method, computer support, inertial sensors, assessment errors*

1. INTRODUCTION

Assessing workload during manual lifting is an important part of industrial ergonomics, especially in tasks involving repetitive lifting, body rotation, and placing objects at different heights. For such tasks, the Revised NIOSH Lifting Equation is often applied to calculate the recommended weight limit (RWL) and the lifting index (LI). RWL depends on the weight of the load and the geometric conditions of lifting, including the horizontal distance H, vertical height V, vertical travel distance D, asymmetry angle A, lifting frequency F, and coupling quality C. LI is calculated as the ratio of the actual load weight to RWL and serves as an indicator of the relative workload of the task [1, 2].

In this paper, the analysis is based on motion measurement using the Perception Neuron 3 (PN3) system, Axis Studio software, and the NAWO Live ergonomic tool. PN3 sensors are inertial measurement units (IMUs) that primarily measure linear accelerations, angular velocities, and, when needed, the magnetic field. Since a single signal is not sufficient for a stable posture estimate, Axis Studio uses sensor data fusion, i.e., algorithmic integration of accelerometer, gyroscope, and magnetometer data to estimate the orientation of the sensor in space. After calibration, the sensors are assigned to body segments, and the movement is displayed on a digital character, i.e., a mannequin. The NAWO Live software then uses the reconstructed movement for ergonomic assessment, including the NIOSH method [3].

It is important to emphasize that IMU sensors do not directly measure joint positions, but primarily the orientation of body segments. Joint positions are reconstructed using a kinematic body model and anthropometric data. The anthropometric model in Axis Studio defines the lengths of the digital skeleton segments, such as the torso, upper arm, forearm, thigh, and lower leg. If an anthropometric model larger than the actual participant is used, distal joints and end points, such as the hand, are reconstructed at a greater distance from the origin joints along the orientation of the segment. If a smaller model is used, the segments are shorter, and the hand is reconstructed closer to the body. The direction of the spatial deviation depends on the current posture, so it cannot be stated in advance that a larger or smaller model will always increase or decrease LI.

In industrial practice, there is often insufficient time to measure each worker's anthropometry precisely, so the closest available male or female height templates are used in Axis Studio. Such an approximation can affect the NIOSH assessment if the positions of the hands, trunk, and load are derived from the digital mannequin. The largest deviations can be expected in the geometric parameters H, V, D, and A, and consequently in the RWL and LI values. The H parameter is particularly important because an increase in the horizontal distance reduces the horizontal multiplier, leading to a lower RWL and a higher LI. According to the available literature, there are fundamental papers on the NIOSH equation and on the validation of Perception Neuron systems. Still, no studies were found that directly examine the influence of an incorrectly selected anthropometric model in Axis Studio on NIOSH results in the NAWO Live software [4, 5]. Therefore, in this paper, this influence is considered as a research question related to the practical industrial approximation of anthropometry [6].

For the analyzed task of lifting paper packages weighing 2.5 kg, it is expected that the model closest to the participant's actual measurements will produce the smallest deviations compared with the reference model. In contrast, models that deviate more substantially from the actual height will have a greater potential to change the reconstructed hand coordinates and lifting geometry parameters. Therefore, the paper aims to determine the extent to which the choice of anthropometric template affects RWL and LI, and whether the use of the closest-height template is sufficiently reliable for practical NIOSH assessment in industrial conditions.

Two hypotheses were formulated to compare results with respect to changes in the dimensions of the anthropometric model:

H0: Anthropometric approximation in the anthropometric model does not indicate a visible descriptive change in RWL and LI;

H1: Different anthropometric models cause visible descriptive changes in RWL and LI.

2. METHODOLOGY

The study used the PN3 motion capture system described in the introduction. It is a wireless system that enables high-reliability full-body motion capture. It consists of 17 inertial sensors and does not require cameras, markers, or a line of sight. Axis Studio v2.12 software was used to control the system and reconstruct the digital model. This software allows entry of the participant's anthropometric measurements, initialization and synchronization of sensors, signal quality checking, calibration, and performance of standard calibration poses (T, S, and A). The software displays the digital model (mannequin) in real time and serves as the starting point for connection with other ergonomic tools. For ergonomic assessment, the HRV NAWO Live software was used, a tool designed to assess the risk of musculoskeletal disorders during physical activities. A Microsoft LifeCam HD-3000 camera was used for video recording. The camera served to monitor and navigate the work scenario, so that the positions and activities to which the obtained kinematic results refer could be clearly determined. The combination of the PN3 system, Axis Studio, and NAWO Live software enabled the collection of kinematic data and their conversion to digital form. The ergonomic parameters displayed in real time served as the basis for analyzing and demonstrating the effects of anthropometric deviations on results and assessments according to the NIOSH method.

The work scenario consisted of repeated individual lifting of ten A4 paper packages, each weighing 2.5 kg. A total of ten consecutive lifts were performed. The package was lifted from a height of 24 cm, passed through the waist level (L5/S1) at 100 cm, and placed on the upper shelf of a cabinet at 164 cm. The coupling was stable and classified as good. The total time for the complete task was approximately 1:25 minutes. In the NAWO Live software, the activity was categorized as lasting less than 1 hour and as repetitive at 8 repetitions per minute. In Axis Studio, a model was created using the actual anthropometric measurements of the measured person. After completing the recording with the newly created 178 cm model, the recording was repeated with the closest standard template, "male180". Two additional identical work scenarios were then repeated using the selected "male165" and "male195" templates, with calibration repeated for each model and the identical work task performed. In this way, three standard templates were included, with deviations of +2 cm and +/-15 cm in relation to the participant's actual height.

The paper packages are 5 cm thick and are stacked in two adjacent columns of five packages each. The lower shelf's basic height is 24 cm. They are lifted and stacked in the same arrangement on a higher shelf with a basic height of 164 cm. Since lifting packages from the lower shelf to waist level (100 cm) changes the height of the lower position from 44 cm to 24 cm. In comparison, the height of the upper shelf position (the lifting action from the waist upward) increases from 164 cm to 184 cm; the first, fifth, and tenth cycles were selected as characteristic work cycles for the analysis. Each cycle was divided into two steps: "Lift 1" (lower shelf to waist level) and "Lift 2" (from the waist to the upper shelf). This approach gives a total of six measurement sequences for comparison (Task 11 to Task 32). The movement phases from Lift 1, stabilization of the load at waist height, and Lift 2 are shown in Figure 1. Workload assessment was performed in the NAWO Live application (Figure 2).



Figure 1: The movement phases

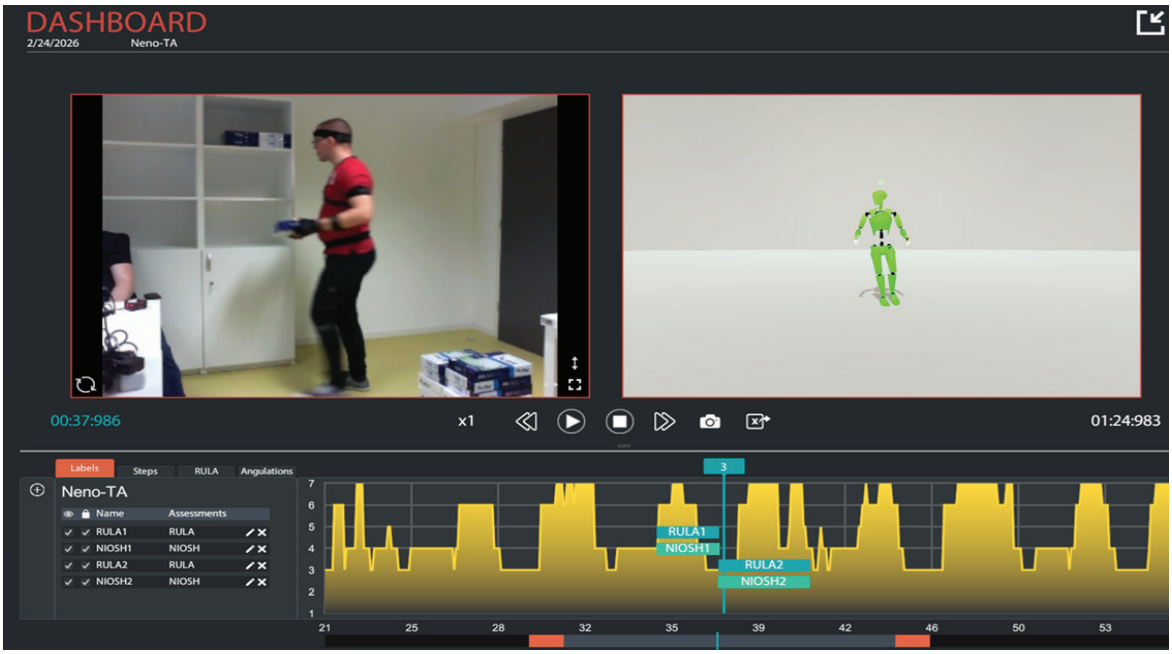


Figure 2: Assessment of workload in the NAWO Live application

Since the method for assessing the permissible load is based on the so-called Revised NIOSH Lifting Equation shown in expression (1), the result of the NIOSH assessment is very sensitive to errors in anthropometric measurements because the recommended weight limit (RWL) is calculated as the product of several correction factors (HM, VM, DM, AM, FM, and CM). Since each factor has a multiplicative effect on the final result, deviations in determining the horizontal distance, grasping height, vertical displacement, or asymmetry angle do not act in isolation; instead, they accumulate. Consequently, even relatively small errors in the assessment of anthropometric parameters can produce significant changes in the calculated RWL and LI, especially in borderline cases when LI is close to 1 [1, 3, 6].

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \quad (1)$$

Descriptive statistical methods were applied in the analysis, and the results indicate trends in changes associated with anthropometric deviations, thereby supporting or not supporting the hypotheses. The number of samples available for inferential statistics is too small. As a compromise, we also acknowledge that it is not possible to perform simultaneous measurements across all four anthropometric models within a single work scenario, which introduces an additional source of uncertainty in the procedure.

3. RESULTS

A comparative overview of the anthropometric dimensions of all four measurement models is presented in Table 1. Disproportionality can be observed between the actual measurements and the dimensions of the predefined templates.

Table 1: Anthropometric measurements of subjects compared to model measurements

Template	M/165	RA-178*	M/180	M/195
Head	15.45	20	16.95	18.4
Neck	9.22	10.5	9.97	10.82
Shoulder width	31	37.5	33.5	36.29
Body	54.09	53	59.34	64.42
Upper arm	25.75	28	28	30.33
Forearm	25.25	26	27.5	29.79
Palm	17	19	18.5	20.04
Hip width	18	20	20	21.67
Upper leg	40.62	40	44.37	48.18
Lower leg	40.62	40	44.37	48.18
Heel hight	7.38	9	8	8.67
Foot length	24	28	26	28.17
Wingspan		177		

*Real anthropometry

Since the complete presentation of results greatly exceeds the available space for this paper, the overall NIOSH results are presented in Table 2, while Tables 3 and 4 show the absolute and percentage differences in NIOSH results by body segment for each approximation model (165, 180, 195) in relation to real anthropometry (RA). The movement phases from sequence 1, step Lift 1, to sequence 3, step Lift 2 are labeled Task 11 to Task 32.

Table 2: Comparative view of RWL and LI for all four models

M/165						
Task	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
RWL	8,15	11,88	10,35	3,19	2,83	2,31
LI	0,31	0,21	0,24	0,78	0,88	1,08
RA-178						
Task	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
RWL	6,92	4,78	10,96	3,56	3,68	2,36
LI	0,36	0,52	0,23	0,7	0,68	1,06
M/180						
Task	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
RWL	7,99	7,53	10,24	2,66	2,73	2,18
LI	0,31	0,33	0,24	0,94	0,92	1,15

M/195						
Task	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
RWL	5,36	10,5	11,65	2,57	2,3	2,04
LI	0,47	0,24	0,21	0,97	1,09	1,23

Table 3: Absolute differences RWL and LI for approximation models

165-RA	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
ΔRWL	1,23	7,1	-0,61	-0,37	-0,85	-0,05
ΔLI	-0,05	-0,31	0,01	0,08	0,2	0,02
180-TA	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
ΔRWL	1,07	2,75	-0,72	-0,9	-0,95	-0,18
ΔLI	-0,05	-0,19	0,01	0,24	0,24	0,09
195-TA	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
ΔRWL	-1,56	5,72	0,69	-0,99	-1,38	-0,32
ΔLI	0,11	-0,28	-0,02	0,27	0,41	0,17

Table 4: Percentage differences RWL and LI for approximation models

165-RA	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
%RWL	17,77	148,54	-5,57	-10,39	-23,10	-2,12
%LI	-13,89	-59,62	4,35	11,43	29,41	1,89
180-TA	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
%RWL	15,46	57,53	-6,57	-25,28	-25,82	-7,63
%LI	-13,89	-36,54	4,35	34,29	35,29	8,49
195-TA	**Task 11**	**Task 21**	**Task 12**	**Task 22**	**Task 13**	**Task 23**
%RWL	-22,54	119,67	6,30	-27,81	-37,50	-13,56
%LI	30,56	-53,85	-8,70	38,57	60,29	16,04

In addition to the absolute differences (Table 3), the percentage deviation values (Table 4) further show that the actual errors are considerably larger than the initially assumed +/-10%, as might be expected based on the available literature [1, 3, 6]. For example, in the 165 cm model, %RWL deviations range from -23.10% to +148.54%, while %LI varies from -59.62% to +29.41%. Similarly, the 180 cm model shows a %RWL range from -25.82% to +57.53% and a %LI range from -36.54% to +35.29%. The largest deviations are observed in the 195 cm model, where %RWL reaches from -37.50% to +119.67%, while %LI ranges from -53.85% to +60.29%. These results clearly show that the deviations are not proportional to the difference in model height and that no rule can be established according to which a larger or smaller anthropometric deviation would predictably increase or decrease the error. On the contrary, the errors are nonlinear and depend on the specific phase of the task, as shown in the accompanying tables.

4. DISCUSSION

The research results show that anthropometric errors among the models have a measurable influence on the calculation of RWL and LI values. In easier tasks (Task 11 and Task 21), deviations were present but moderate. Even in the face of these small differences, it was shown that average models produce more favorable LI values, which may lead to an underestimation of the risk to which the worker is exposed. In the intermediate phases of the task (Task 12 and Task 22), the differences become more pronounced. Models of different heights show different RWL and LI values, and the largest deviations occur in the 180 cm and 195 cm models. This confirms that the proposed average models affect the multipliers in the NIOSH equation. The greatest differences were observed in the most demanding phases (Task 13 and Task 23), where the load is lifted to a greater height. In these data, all models produce low RWL values. The model with real anthropometry crossed the threshold in Task 23, while the 195 cm model crossed the threshold in Task 13 and had a higher LI in Task 23.

Overall, these results show that anthropometric approximations can lead to risk assessment errors, either underestimating or overestimating risk. For more methodologically reliable results, it would be necessary to conduct recordings with clearly defined, consistently repeated movement sequences performed in as similar or almost identical a manner as possible. In addition, including a larger number of participants and repetitions would allow the application of inferential statistics, thereby increasing the validity and generalizability of the conclusions [7].

The presented results support hypothesis H1, which posits that deviations in anthropometric measurements from actual values cause visible descriptive changes in RWL and LI. Deviations in body height and proportions affect the multipliers in the NIOSH equation, which, in turn, alter RWL and LI values.

5. CONCLUSION

This paper aimed to investigate whether anthropometric errors influence workload assessment using the NIOSH method. The experimental results clearly showed that errors in anthropometry can lead to significant deviations in the calculation of RWL and LI. Although the differences were moderate in the simpler phases, the deviations were more noticeable in the more complex phases of the work.

Comparing the participant's actual anthropometry with average models at 165 cm, 180 cm, and 195 cm showed that incorrect body height and proportions affect the multipliers in the NIOSH equation. Since RWL is calculated by multiplying several multipliers, even a small error in worker anthropometry can lead to incorrect results. This is particularly evident in Tasks 13 and Task 23, where LI values in the provided average models are higher than those in the model with real anthropometry, which could lead to an incorrect conclusion in workload assessment. Based on this research, it can be concluded that the null hypothesis, according to which anthropometric approximations do not significantly affect RWL and LI, is not supported. For the alternative hypothesis H1, which posits that different anthropometric models cause changes in RWL and LI, the observed deviation trends support it in an indicative sense. This leads to the conclusion that accurate anthropometry is a key prerequisite for the reliable and accurate use of the NIOSH equation.

The practical value of this research lies in the experimental finding that average models in Axis Studio, although useful, can produce incorrect results. In industrial applications where there is insufficient time for continuous, repeated measurement of each worker's anthropometric parameters and where average models are therefore used, there is a real risk that the exposure to which the worker is exposed may be underestimated or overestimated, which can affect worker safety and health. Therefore, when using mocap systems, it is recommended that the worker's actual anthropometric dimensions always be entered. Digital tools such as PN3/Axis Studio and NAWO Live have great potential for modern ergonomics, but their accuracy and effectiveness depend on the quality of the input data.

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Professional paper

ERGONOMIC DESIGN OF SEDENTARY WORKSTATIONS IN THE PREVENTION OF MUSCULOSKELETAL DISORDERS

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Abstract: *Musculoskeletal disorders (MSDs) represent a leading cause of work disability and pose a significant burden on modern work environments, particularly in occupations characterised by prolonged sitting. Prolonged sitting increases biomechanical loading of the spine, alters muscle activation patterns, and reduces movement variability, contributing to the development of pain and functional limitations. The key issue of sedentary work is not merely improper posture, but prolonged static exposure.*

The aim of this paper is to analyse the biomechanical mechanisms of sedentary work and to evaluate the role of ergonomic design of sedentary workstations in the prevention of MSDs.

The paper is based on a narrative review of contemporary scientific and professional literature in the fields of ergonomics, biomechanics, and occupational safety and health.

The findings indicate that ergonomic adjustments reduce biomechanical loading; however, ergonomics alone does not represent an effective strategy for preventing MSDs. More effective approaches include breaking up prolonged sitting and increasing movement variability.

The paper emphasises the need for integrated preventive strategies that go beyond traditional ergonomic approaches and are essential for the design of modern work environments.

Keywords: *ergonomics, sedentary work, musculoskeletal disorders, biomechanical load, prevention*

1. INTRODUCTION

Musculoskeletal disorders (MSDs) are among the leading causes of reduced work ability, sickness absence, and disability. They represent a substantial burden for individuals, employers, and healthcare systems alike. In modern work environments, the risk of developing MSDs is increasingly associated with sedentary work, which has become the predominant form of work in many occupations [1]. A Slovenian study showed that more than half of administrative workers

spend over 10 hours per day sitting, confirming the magnitude of this problem in the national context as well [2].

Sedentary behaviour is defined as any waking activity performed in a sitting, reclining, or lying posture with an energy expenditure not exceeding 1.5 metabolic equivalents (METs) [3]. Prolonged sitting is associated with an increased risk of low back pain, neck pain, and shoulder discomfort and represents an important risk factor for the development of MSDs [1]. In addition to musculoskeletal consequences, sedentary behaviour is also associated with an increased risk of cardiovascular disease, type 2 diabetes, and premature mortality [4].

Work-related MSDs associated with sedentary work arise from a complex interaction of biomechanical, organisational, and individual factors. Among the biomechanical factors, important roles are played by alterations in spinal loading, increased pressure on intervertebral discs, prolonged static muscle activation, and reduced movement variability [5, 6]. Understanding these mechanisms provides the foundation for the development of effective ergonomic measures and other preventive strategies in the workplace.

Traditional ergonomic approaches have primarily focused on optimising posture and adapting the workstation to the individual. In recent years, however, increasing evidence has shown that the key problem of sedentary work is not merely poor posture but prolonged static exposure [7, 8, 9, 10, 11]. Even a workstation that is appropriately adjusted in terms of chair, monitor, and work surface settings cannot eliminate the adverse effects of prolonged uninterrupted sitting [8, 10, 11]. Therefore, contemporary approaches to MSD prevention emphasise not only ergonomic workstation design but also the reduction of uninterrupted sitting time and the promotion of movement variability during work.

The aim of this paper is to analyse the biomechanical mechanisms of sedentary work and to evaluate the role of ergonomic workstation design in the prevention of MSDs. Attention is given to current evidence regarding the effectiveness of ergonomic interventions, their limitations, and their implications for occupational safety and health.

2. BIOMECHANICAL BASIS OF SEDENTARY WORK

2.1. Biomechanical changes during prolonged sitting

Prolonged sitting represents a specific biomechanical load that substantially alters the position of body segments and the distribution of forces within the musculoskeletal system. One of the most characteristic changes is a posterior pelvic tilt of approximately 18°. Consequently, physiological lumbar lordosis decreases by up to approximately 50% compared with standing when an individual sits upright without backrest support [5]. A reduction in lumbar lordosis alters the distribution of loads among the passive structures of the spine (e.g. ligaments, intervertebral discs) and the paraspinal muscles. Changes in the lumbar region also affect other spinal segments. Thoracic kyphosis increases, while the cervical spine often compensates through a forward head posture, thereby altering the biomechanics of the entire spinal column [5].

Changes in pelvic and spinal alignment also influence the biomechanical conditions under which muscles function during sitting. Hip and knee flexion angles increase, the hip flexor muscles assume a relatively shortened position, and the hip extensors are placed in a lengthened position. At the

same time, the demand for static muscle activity increases, particularly in the back extensors and the muscles of the neck and shoulder region. Prolonged static activation reduces muscle blood flow, accelerates the development of muscle fatigue, and may contribute to pain and feelings of discomfort [5, 11, 12].

Another important biomechanical factor associated with sedentary work is the increased loading of the intervertebral discs. The first measurements of intradiscal pressure were performed by Nachemson, who demonstrated that lumbar disc loading increases during sitting compared with standing. Subsequent studies have shown that intradiscal pressure depends on trunk position and the characteristics of the sitting posture. A systematic review and meta-analysis [6] confirmed that intradiscal pressure in the lumbar spine is, on average, higher during sitting than during standing. The increase is particularly pronounced during slumped sitting and prolonged maintenance of the same posture.

In addition to their mechanical role, intervertebral discs have an important metabolic function. Because of their limited vascular supply, disc nutrition depends primarily on the diffusion of nutrients through the cartilaginous endplates. Alternating loading and unloading plays a key role in this process by facilitating nutrient transport and the removal of metabolic waste products. Prolonged static exposure reduces the efficiency of this physiological mechanism and may contribute to less favourable conditions for maintaining normal disc function, further emphasising the importance of reducing uninterrupted sitting time [5].

Although most studies on the biomechanics of sitting focus on the lumbar spine, evidence indicates that prolonged sitting is also associated with reduced thoracic spine mobility [13]. Reduced thoracic mobility may affect the movement of adjacent spinal segments and contribute to the development of compensatory movement patterns.

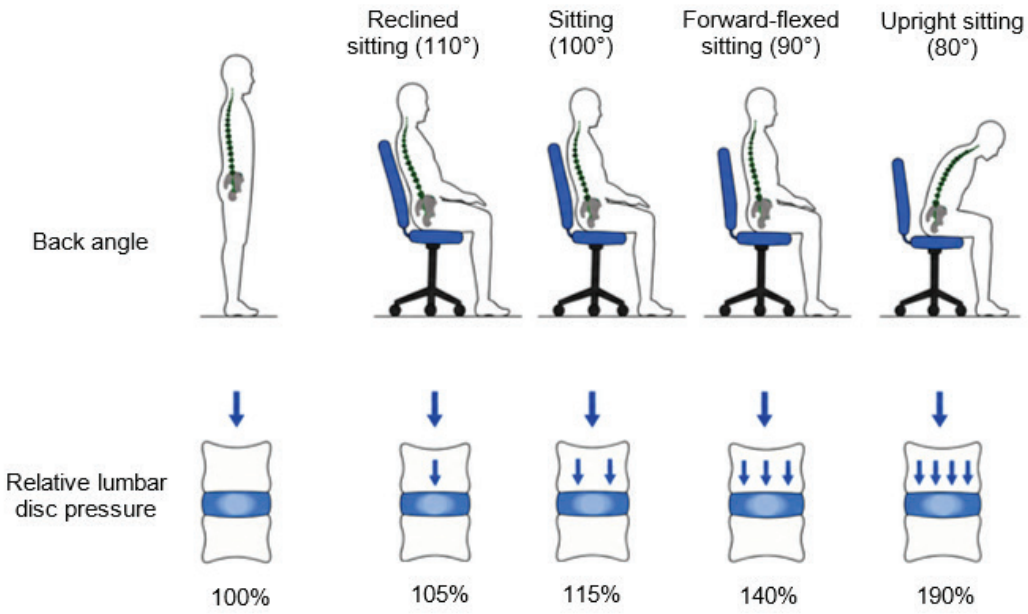


Figure 1: Influence of trunk position on lumbar disc pressure (adapted from Mountain Physiotherapy [14]).

2.2. Static loading and movement variability

Prolonged sitting requires continuous low-intensity activation of the postural muscles responsible for maintaining trunk and head position. The muscles of the neck and shoulder region, as well as the lumbar extensors, are particularly affected, and an association has been reported between prolonged sitting and the development of musculoskeletal complaints in these muscle groups [1, 5, 12].

Contemporary research emphasises that the risk of developing MSDs during sedentary work is not determined solely by the magnitude of biomechanical loading, but also by prolonged exposure to repetitive loading patterns and the lack of load redistribution [5, 11, 12]. Sustained exposure to similar loads limits the redistribution of forces among different anatomical structures and increases the cumulative loading of individual tissues.

Even a biomechanically favourable posture cannot prevent tissue overload when maintained for prolonged periods. Consequently, modern ergonomics increasingly emphasises the importance of movement variability and regular changes in body position during work [11, 12]. Movement variability refers to an individual's ability to spontaneously alter body positions and redistribute mechanical loads among different anatomical structures throughout the working day. This reduces the cumulative loading of specific tissues and promotes greater biomechanical diversity during work [5].

For this reason, contemporary approaches to ergonomic workstation design increasingly focus on creating adaptable work environments, reducing uninterrupted sitting time, and providing conditions that enable workers to change positions regularly and achieve greater biomechanical variability during work [7, 9, 11, 12].

3. ERGONOMIC DESIGN OF SEDENTARY WORKSTATIONS

3.1. Ergonomic principles of workstation design

Ergonomics is an interdisciplinary field that examines the adaptation of the work environment to the individual with the aim of improving safety, health, efficiency, and comfort at work. The fundamental principle of ergonomic workstation design is to align job demands with an individual's physical and functional capabilities to minimise unnecessary biomechanical loading and reduce the risk of developing work-related MSDs [15].

In sedentary work, the objective of ergonomic design is to create a work environment that enables the maintenance of favourable body positions, reduces awkward postures, and supports the efficient performance of work tasks. An ergonomically designed workstation minimises the need for extreme joint ranges of motion, excessive reaching of the upper limbs, and prolonged static loading of individual anatomical structures [5, 15].

Contemporary ergonomic approaches emphasise that the workstation must be adaptable to the user. Due to differences in body dimensions, anthropometric characteristics, and job requirements, it is not possible to design a universal workstation suitable for all employees. Therefore, adjustable workstation components play an important role in enabling individual adaptation of the work environment [15, 16].

Despite the important role of ergonomic design, current evidence indicates that workstation adjustments alone cannot eliminate the adverse effects of prolonged sitting. Ergonomics should therefore be regarded as one component of a comprehensive approach to the prevention of MSDs and the promotion of health in the workplace [7, 8, 9].

3.2. Key ergonomic components of a sedentary workstation

For computer-based work, the workstation should be adjustable and allow the maintenance of neutral joint positions. Appropriate adjustment of the chair, work surface, monitor, and input devices reduces the need for awkward postures and contributes to a more favourable distribution of biomechanical loads during work [15, 16].

The chair height should be adjusted so that the feet are fully supported on the floor or on a footrest, the knees are flexed to approximately 90–100°, and the hips are at the same level as or slightly higher than the knees. The seat depth should allow approximately 2–5 cm of space between the front edge of the seat and the back of the knees. An excessively deep seat increases pressure in the popliteal region, reduces support for the lumbar spine, and forces the user to sit at the edge of the chair. A chair that is too low increases hip flexion and promotes posterior pelvic tilt, contributing to a reduction in lumbar lordosis and increased loading of the passive structures of the lumbar spine. The backrest should support the lumbar region and allow a slightly reclined sitting posture, with an angle of approximately 100–120° between the seat surface and the backrest. Such a position reduces loading on the intervertebral discs compared with upright sitting without backrest support. Armrests should provide relaxed support for the forearms without elevating the shoulders, thereby reducing static loading of the neck and shoulder muscles [5, 15, 16].

The work surface should be adjusted to match the chair height so that the upper surface of the desk is approximately at elbow level. In this position, the elbows are flexed to approximately 90–120°, the shoulders remain relaxed, and the forearms are supported. A desk that is too high causes shoulder elevation and increased tension in the neck and shoulder muscles, whereas a desk that is too low promotes a slouched posture and increases loading of the lumbar spine. The keyboard and mouse should be positioned directly in front of the user and as close to the body as possible. Input devices placed too far away increase loading of the shoulder girdle and require prolonged static activation of the neck and shoulder muscles. Frequently used work items should be located within forearm reach to minimise the need for excessive reaching, shoulder abduction, trunk rotation, and forward leaning [15, 16].

The monitor should be positioned directly in front of the user, with the top edge of the screen at or slightly below eye level. The recommended viewing distance is approximately 50–70 cm, or about an arm's length. A monitor positioned too low promotes prolonged cervical flexion, whereas a monitor positioned too high increases cervical extension. Both situations increase loading of the cervical spine and the neck and shoulder muscles. When two monitors are used, the primary monitor should be placed directly in front of the user to minimise cervical rotation during work. For prolonged laptop use, an external keyboard, mouse, and preferably an additional monitor is recommended, as the use of a laptop alone often results in simultaneous cervical flexion and increased loading of the upper limbs [16].

In addition to the physical arrangement of the workstation, lighting and indoor environmental conditions are also important. Insufficient lighting, glare, and reflections on the monitor increase visual strain. As a result, employees often move closer to the screen or alter their head position, which may increase loading of the cervical spine and the neck and shoulder muscles [15, 16]. Workplace

comfort is also influenced by indoor environmental conditions. For office work, a temperature between 20 and 25 °C and a relative humidity between 40 and 70% are recommended, as unfavourable conditions may increase fatigue, reduce concentration, and impair work performance [17].

Contemporary ergonomic workstation design extends beyond the proper adjustment of individual pieces of equipment. Increasing emphasis is placed on the adaptability of the work environment, enabling employees to change working positions and reduce uninterrupted sitting time. Such solutions reduce prolonged static exposure and provide greater flexibility in the organisation of work [7, 9, 18].

3.3. Effectiveness and limitations of ergonomic interventions

Numerous studies have demonstrated that ergonomic interventions can reduce biomechanical loading during sedentary work and improve employee comfort. Appropriate workstation adjustments reduce the need for awkward body positions, promote a more favourable distribution of mechanical loads, and contribute to the reduction of certain risk factors associated with the development of work-related MSDs [15, 16].

Ergonomic interventions encompass a variety of measures, which may be classified as educational, organisational, or environmental approaches. Their primary objective is to reduce workplace risk factors and promote healthy work habits among employees [17]. In practice, ergonomic measures are often implemented in isolation, either as modifications of the physical work environment or as interventions aimed at changing employee behaviour.

Despite the positive effects of individual ergonomic measures, systematic reviews and meta-analyses indicate that isolated interventions have only a limited impact on reducing the prevalence of MSDs. Greater effectiveness is achieved through comprehensive approaches that combine multiple types of interventions and simultaneously address different workplace risk factors [7, 8, 9].

Effective prevention of MSDs therefore requires an interdisciplinary approach and collaboration among various professionals in the planning and implementation of workplace health and safety programmes.

3.4. Role of the physiotherapist in workplace ergonomics

Physiotherapists play an important role in the prevention and management of work-related MSDs. Owing to their knowledge of biomechanics, ergonomics, and musculoskeletal function, they can contribute to the identification of workplace risk factors, ergonomic workstation assessments, and the development of measures aimed at reducing biomechanical loading among employees [19].

An important aspect of their work is the education of employees regarding appropriate workstation organisation, the correct use of work equipment, and the importance of preventing prolonged static loading. Physiotherapists may also participate in the planning and implementation of preventive programmes designed to reduce the risk of developing MSDs and to promote healthy work habits [19].

As the development of MSDs is influenced by numerous interrelated factors, their prevention requires a comprehensive approach. Through their expertise, physiotherapists can make a significant contribution to workplace health promotion initiatives and to the development of safer and healthier work environments [19].

4. CONCLUSION

Sedentary work represents a significant risk factor for the development of MSDs, as prolonged sitting alters spinal biomechanics, increases static tissue loading, and reduces movement variability. Although ergonomic workstation design can substantially reduce biomechanical demands and improve working conditions, it is not sufficient on its own to eliminate the adverse effects of prolonged sitting.

Current evidence indicates that effective MSD prevention requires a comprehensive approach that extends beyond traditional ergonomic adjustments and includes strategies aimed at reducing uninterrupted sitting time and promoting movement throughout the working day. In this context, physiotherapists play an important role in the planning and implementation of preventive measures, contributing their expertise in biomechanics, ergonomics, and MSD prevention to the development of safer and healthier workplaces.

The key message of contemporary ergonomics is not the pursuit of a single optimal sitting posture, but the creation of work environments that encourage regular postural changes, greater movement variability, and reduced exposure to prolonged uninterrupted sitting. Such an approach provides a more effective foundation for the prevention of MSDs and the promotion of long-term occupational health.

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Original scientific paper

DESIGN OF FUNCTIONAL CLOTHING ELEMENTS BASED ON DYNAMIC ANTHROPOMETRIC ANALYSIS OF DIFFERENT FEMALE BODY TYPES

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Abstract: *This paper presents a methodology for the design of functional clothing elements based on the analysis of dynamic anthropometry across different female body types. A sample of test subjects was classified into representative body types using 3D body scanning analysis. Body deformations were recorded using an optical 3D measurement system, allowing full-field analysis of surface strain during movement. Key functional postures were analysed to identify critical deformation zones. The obtained data were integrated into digital pattern design and construction and used to develop a 3D virtual prototype of a functional work jumpsuit. Garment behaviour was evaluated through 3D simulations under dynamic conditions, and the results revealed significant differences in deformation patterns between body types, particularly in the back, hip, and thigh regions. The study demonstrates that incorporating dynamic anthropometric data significantly enhances garment fit and functional performance.*

Keywords: *functional clothing, dynamic anthropometry, body deformations, digital 3D prototype*

1. INTRODUCTION

The design and development of contemporary clothing systems increasingly rely on interdisciplinary approaches that integrate textile engineering, digital technologies, and human-centered design principles. Traditionally, garment construction has been based on static anthropometric measurements, which represent the human body in a static, neutral posture. While such approaches have proven effective for basic sizing systems, they are insufficient for capturing the complex and continuous changes in body dimensions that occur during movement. As a result, garments designed using static data often fail to meet high requirements for fit and functionality in real-use conditions, particularly in applications requiring enhanced mobility or performance [1].

To address these limitations, the field of dynamic anthropometry has gained increasing attention. Dynamic anthropometry focuses on the measurement and analysis of body dimensions during motion, providing insight into how the human body deforms and adapts under dynamic conditions. Early research emphasized the importance of incorporating movement-related measurements into garment design, particularly for protective and functional clothing [2-4]. Advancements in 3D and 4D body scanning technologies have further accelerated research in this field. Modern scanning

systems allow for high-resolution capture of body geometry in both static and dynamic states, supporting the development of kinematic human models capable of simulating realistic movement patterns [5,6]. Such models are essential for analysing garment fit in motion, as they provide a digital representation of the body and motion that can be integrated into software for the development of digital garment prototypes. The introduction of motion-aware avatars has significantly improved the ability to predict garment behaviour during dynamic activities, although challenges remain in accurately replicating complex biomechanical interactions.

3D virtual prototyping has emerged as a transformative tool in the apparel industry. Virtual garment simulation enables designers to visualize, evaluate, and modify clothing without the need for physical prototypes. Numerous studies have explored the capabilities and limitations of virtual prototyping systems, highlighting their potential for improving design efficiency and sustainability [7]. However, the accuracy of these systems depends heavily on the fidelity of input parameters, including fabric mechanical properties, body geometry, and motion definitions.

In addition to technological challenges, garment design must also account for the diversity of human body types. Female body morphology, in particular, exhibits significant variability in shape and proportions, which directly influence garment fit and deformation behaviour. Previous research has emphasized the importance of incorporating morphological diversity into sizing systems and design methodologies to ensure inclusivity and functionality [8]. However, the integration of dynamic anthropometric data specific to different body types remains limited, highlighting an important gap in current research. Recent studies have explored approaches to garment design that combine experimental data, digital simulation, and material characterisation. The use of different systems for determining fabric mechanical properties enables more accurate input parameters for simulation models [7]. Such an approach supports the development of predictive models capable of accurately representing garment behaviour under dynamic conditions.

Building on these advancements, this research proposes a comprehensive methodology that integrates dynamic anthropometric analysis of the human body, the application of dynamic anthropometric data in garment design and construction, the development of digital clothing prototypes and the analysis of body deformations during different movements. The integration of dynamic data into the garment design process represents an upgrade from static, experience-based approaches toward data-driven, engineering-oriented methodologies. Such advancements are essential for the development of next-generation clothing systems that meet the demands of performance, comfort, and adaptability in increasingly complex use environments.

2. METHODOLOGY

2.1. Classification of Female Body Types

Female body types were classified based on a sample of 126 scanned 3D body models and a previously established method for body shape classification. Based on the relationship between characteristic width and height measurements in the frontal plane, the method distinguishes three body types: rectangular, hourglass, and hourglass with a pronounced lower body part [8]. Three representative test subjects (I1, I2, I3) were selected for further analysis, each corresponding to one of the defined body types. While all subjects belonged to the same clothing size, their morphological differences enabled comparative analysis of deformation behaviour in motion.

2.2. Dynamic Anthropometry and Body Deformation Analysis

Five body movements were selected and recorded using the Aramis optical 3D measurement system for the analysis of dynamic deformations: arms spread (P0), arms forward (P2), arms up (P3), forward bend (P4) and squat (P5). The recorded data were processed to generate 3D measurement surfaces and coordinate system was adjusted on separated body surface segments, to correspond to the warp and weft directions of the textile material. The coordinate system adjustment enables the tracking of dynamic body deformations with respect to clothing design and pattern construction. For more precise deformation analysis and application of the research results in clothing development process, a grid of characteristic body/clothing lines was created, enabling the direct mapping of body deformation zones to the garment pattern, Figure 1.

Maximum surface deformations were analysed in the transverse and longitudinal directions for five selected movements and three different body types. Along with the transverse (x) and longitudinal (y) deformations, particular body zones showed significant changes in the z axis directions, such as the back body segment during the arms forward movement (P2), in which the entire scapula region moved backwards along the z axis by more than three centimeters. The same deformation effect occurred in the biceps (P1 to P3) and thigh regions (P4 and P5), as well as the knee joints during squatting (P5). The determined data were integrated into the design and construction process of work jumpsuit model. While the transverse and longitudinal deformations can be accommodated by adjusting the garment pattern through additional ease allowances in particular areas, the observed deformations in the z direction either require additional ease, which can lead to oversizing, or can be addressed through specific design elements and construction solutions, such as the incorporation of inner folds and pleats, Figure 2.

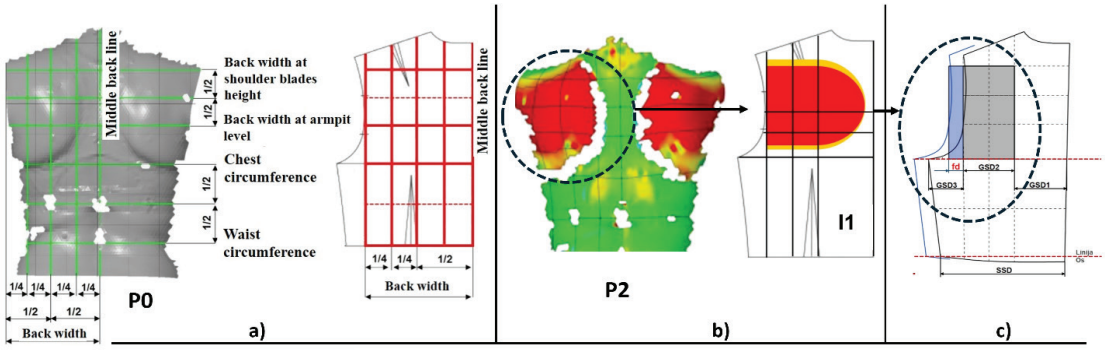


Figure 1: Analysis of body deformations: a) grid of characteristic body/clothing lines on body surface, b) mapping body deformation on garment pattern, c) adjustment of garment pattern based on deformation value

2.3. Digital Garment Design and Simulation

Based on the identified deformation zones, a digital pattern of a work jumpsuit was designed and developed to meet the high functional demands under dynamic conditions. The design and construction of work jumpsuit included double folded pleats in garment areas corresponding to the zones of maximum body deformation in the z direction, Figure 2b and 2c, as well as the calculation of additional ease allowances to accommodate the transverse and longitudinal deformations of different body types during movement. As a reference clothing model for fit analysis, a standard work jumpsuit was digitally developed using a traditional construction methodology, Figure 2a.

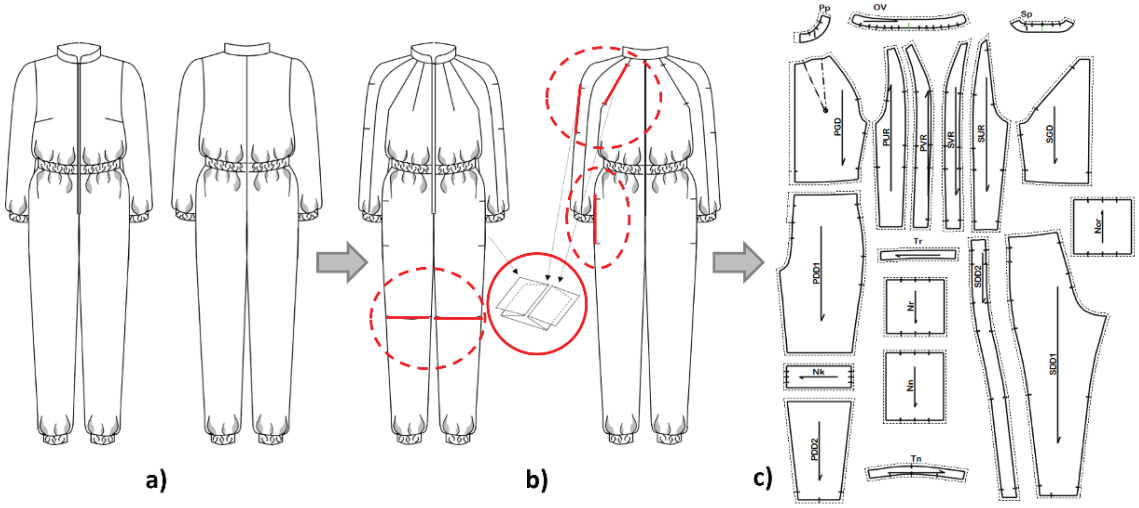


Figure 2: Design of functional work jumpsuit: a) reference standard work jumpsuit constructed using traditional construction method (M1), b) work jumpsuit designed with functional elements positioned in critical deformation zones (M2), c) 2D pattern of functional work jumpsuit (M2)

The garments were simulated in CLO software using avatars adjusted according to the anthropometric characteristics of scanned 3D models representing three different body types. The physical and mechanical properties of the selected woven fabric were tested using different methods: Kawabata Evaluation System (KES-FB) [9], SEDDI Textura AI technology [10] and standard tensile breaking test [11]. SEDDI Textura parameters were used for development of digital prototypes and 3D garment simulations on bodies in motion, Table 1. Parameters obtained using the KES-FB system and standard method were used to establish an evaluation scale for assessing the fit and functionality of the digital prototypes, Table 2.

Table 1: Physical and mechanical parameters for 3D simulation determined using SEDDI Textura AI

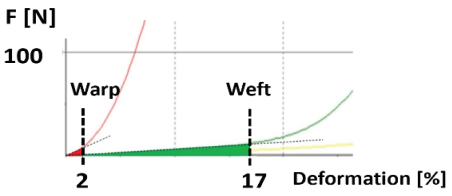
Woven fabric 97% cotton 3% elastane	Specific weight	Thickness	Tensile stretch [g/s²]		Shear rigidity	Bending rigidity [gmm²/s²]		
	W [g/m²]	d [mm]	warp	weft	G [g/s²]	warp	weft	bias
F1	226.58	0.52	691472	425985	89210	4651	2578	2822

2.4. Fit Analysis of Digital Prototypes under Dynamic Conditions

The performance of both digital prototypes was analysed using animated body models performing the same five movements as those used in the anthropometric analysis. The critical fit zones were identified by tracking clothing deformations in the warp and weft directions throughout the movements. The obtained deformation values at the final positions of the respective movements were assessed using the defined evaluation scale, in which fabric testing results obtained using KES-FB were defined as normal/allowed deformations (marked in blue shades). The boundary of the linearity range and breaking deformation, obtained from standard tensile testing diagram, were defined as the critical zone (marked in yellow shades) and the unallowed/breaking zones (marked in red shades), Table 2.

Table 2: Defined fit evaluation scale and tensile F/ε diagram with marked linearity range

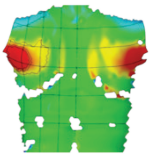
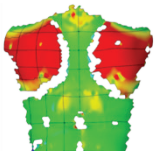
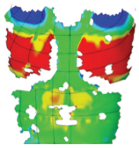
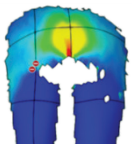
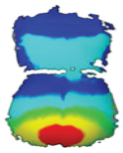
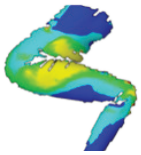
Reference deformation values for fit assessment					
ε_x [%]	0	1.6	2	8	15
ε_y [%]	0	11	17	40	64



3. RESULTS

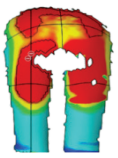
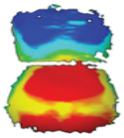
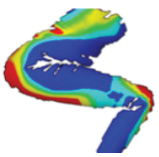
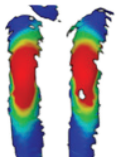
The research results confirm that body deformations during movement are strongly influenced by both body morphology and the specific movement performed. During the arm movements (P1 and P2), the highest transverse deformation occurred in the back region, particularly at the armpit level, confirming this area as critical for garment mobility, Table 3.

Table 3: Values of transverse (x) deformations of different body types in relevant body movements

	Maximum values of transverse deformations, ε_x [%]					
						
	P1	P2	P3	P4	P5	
I1	33.59	34.54	30.31	15.05	19.21	14.05
I2	27.71	37.39	40.97	14.63	18.60	7.83
I3	23.33	30.48	28.15	14.94	16.05	12.02

During the forward bending movement (P4), longitudinal deformations reached up to 33%, particularly along the back and posterior leg regions, Table 3, while combined transverse and longitudinal deformations were observed during squatting (P5), with pronounced deformation in the hip and thigh areas, Table 3 and 4. Despite the identical clothing size of the analysed test subjects, deformation values differed significantly among the different body types, confirming the importance of body shape classification. Garment simulations and analysis of the digital prototypes under dynamic conditions revealed that critical body deformation zones corresponded to areas of increased garment deformation across all three body types. Standard pattern construction did not completely accommodate these variations, whereas integration of dynamic data into the garment development process significantly improved functionality and fit, Figure 3.

Table 4: Values of transverse (x) deformations of different body types in relevant body movements

	Maximum values of longitudinal deformations, ε_y [%]					
						
	P3	P4		P5		
I1	36.66	33.01	25.04	21.11	23.16	25.70
I2	37.29	26.81	23.94	21.22	19.71	27.94
I3	30.61	21.54	20.33	23.58	20.98	29.76

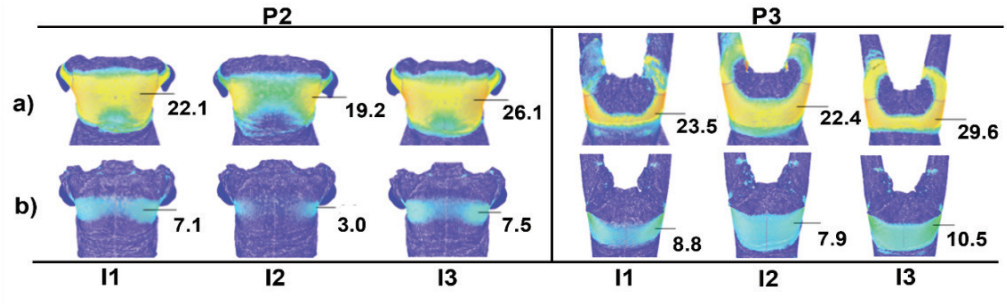


Figure 3: Digital prototypes analysis in arm movements (P1, P2 and P3) on three different body types: a) reference work jumpsuit, constructed using traditional methodology (M1), b) work jumpsuit designed and developed based on dynamic anthropometry data (M2)

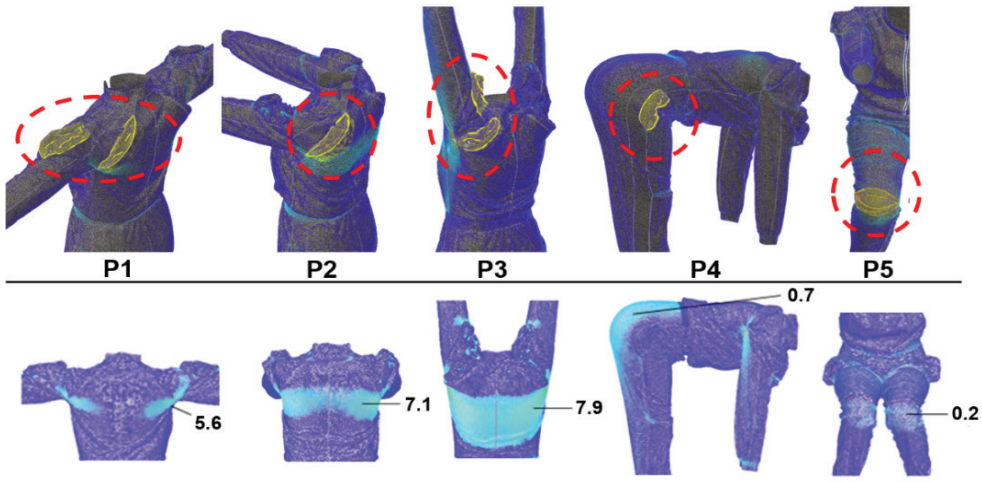


Figure 4: Evaluation of work jumpsuit model M2 in five body motions on the test subject I1

As shown in Figure 4, the double folded pleats incorporated into the pattern of work jumpsuit model M2 provided additional ease in areas of maximal deformability during specific movements and confirmed their functionality and effectiveness. In areas with observed deformations in the z directions, double folded pleats opened to release additional area, thereby allowing unrestricted body surface deformation. Evaluation of M2 digital prototype model showed a high fit assessment across all five analysed movements, Figure 4.

4. CONCLUSIONS

The presented research confirms the importance of dynamic anthropometry in functional clothing design. Traditional static approaches are insufficient for designing garments that meet functional requirements under dynamic conditions. The application of optical 3D measurement systems enables detailed analysis of body deformation zones during motion, providing valuable input data for pattern design and the development of new clothing models. The integration of these data with the analysis of digital 3D clothing prototypes enables the development of garments with improved functionality and fit. Future research will focus on expanding the range of garments and relevant movements analysed and on integrating the behavior of different textile materials into simulation models.

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Original scientific paper

ERGONOMIC RISK CONTROL IN MANUAL ELECTRIC MOTOR ASSEMBLY

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Abstract: *Electric motor manufacturing in small and medium-sized enterprises (SMEs) still includes manual subassembly operations in which precision fastening, visual inspection and component handling may create cumulative ergonomic risk. This anonymized before-and-after case study evaluates a manual electric-motor subassembly workstation using OWAS (Ovako Working Posture Analysis System) observation, process-flow recording, a 5S (Sort, Set in order, Shine, Standardize, Sustain) workplace-organization audit and hierarchy-of-controls interpretation. Baseline exposure showed approximately 60% elevated upper-arm posture and 57% forward-inclined head posture during active work. The workplace redesign introduced an adjustable work surface, locating fixture, suspended torque screwdriver, improved lighting, optimized reach zones and organized component supply. After redesign, elevated upper-arm posture decreased to 46%, forward head inclination to 39%, the 5S audit reached 23/25 points and operation time decreased from 5:23 to 4:15. The case confirms that practical ergonomic redesign can serve as an effective preventive occupational safety measure in SME electric motor manufacturing.*

Keywords: *electric motor assembly; ergonomics; manual assembly; OWAS; workstation redesign*

1. INTRODUCTION

Occupational safety in manufacturing is commonly associated with immediate accident hazards such as moving machinery, sharp edges, electrical energy, slips and falling objects. In manual assembly, however, an important part of risk develops gradually through cumulative biomechanical exposure. A worker may complete a shift without an incident and still experience substantial physical load due to repeated neck flexion, elevated shoulder posture, static standing, unsupported tool

use and visually demanding precision work. For this reason, ergonomics should be treated as an integral part of occupational safety and health (OSH), rather than only as a comfort or productivity issue [1,2].

This paper presents an anonymized ergonomic case study of a manual electric-motor subassembly workstation. The measured exposure indicators are preserved, while company- and product-specific details are generalized to protect sensitive operational information. Figure 1 places the analysed workstation between component preparation and final motor assembly.

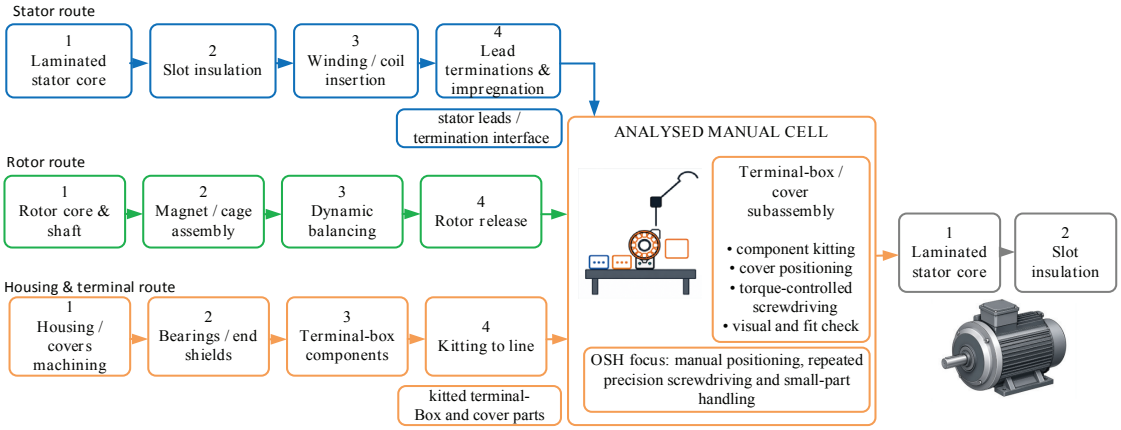


Figure 1: Position of the analysed manual subassembly workstation within the electric motor assembly process.

Manual electric motor assembly in small and medium-sized enterprises (SMEs) provides a realistic industrial context for this type of ergonomic intervention. Although large-scale motor production is often highly automated, manual and semi-automated operations remain common in winding, terminal connection, terminal-box assembly, cover and end-shield preparation, sensor installation, final assembly and end-of-line verification [3]. These operations combine small-part handling, torque-controlled fastening, visual alignment and traceability requirements under repetitive manual work conditions. Poor workstation design can therefore affect both worker exposure and assembly quality.

2. SCIENTIFIC AND PROFESSIONAL BACKGROUND

Three literature streams support the case. First, ergonomics is a systems discipline that links people, tasks, tools, technology, organization and environment [1]. Second, OSH management systems and the hierarchy of controls require risk reduction at the source whenever feasible [2,5]. Third, recent manufacturing research increasingly frames assembly design as worker-centred, digitally supported and Industry 5.0-oriented, while continuing to emphasize the importance of practical ergonomic improvements [8-10].

In electric motor assembly, recent studies report improvement potential through one-piece flow, ergonomics and cellular layout [4], as well as flexible assembly-line planning for high-efficiency motors [11]. The present case focuses on a manual electric-motor subassembly workstation in which terminal-box or cover subassembly is performed before final integration. These operations

involve repetitive fastening, visual alignment and small-part handling under constrained workspace conditions. Table 1 summarizes the associated ergonomic risk mechanisms and their potential OSH consequences.

Table 1: Representative electric-motor subassembly operations and ergonomic risk mechanisms

Operation	Typical components/tools	Ergonomic exposure mechanism	Possible OSH and quality consequence
Component kitting	Screws, washers, gaskets, terminals, labels	Searching, reaching and low-level picking	Fatigue, wrong component selection, unstable rhythm
Positioning in fixture	Terminal box, cover plate, locating pins	Forward head inclination during visual alignment	Neck load, misalignment, rework
Fastening sequence	Powered torque screwdriver and screws	Upper-arm abduction and static shoulder load	Shoulder overload, less repeatable fastening posture
Visual inspection	Subassembly, label, checklist	Neck flexion and visual concentration	Missed defects, repeated correction loops

3. METHODOLOGY

The study was conducted as a before-and-after ergonomic workstation case study. The methodology included baseline assessment, workstation redesign and post-intervention verification. OWAS observation was performed every 20 seconds during 240 minutes of active work, resulting in 720 posture records. The observed categories included back posture, upper limbs, wrists, lower limbs, head/neck position and external force. The same observation procedure was applied before and after redesign to enable direct comparison of posture exposure [6,7].

Process-flow recording was used to identify unnecessary movement and to measure operation time. A 5S workplace-organization audit assessed workstation order and standardization after redesign. Worker feedback was additionally used to evaluate the practical usability of the redesigned workstation. Table 2 summarizes the applied methods and their ergonomic relevance.

Table 2: Applied methods and their ergonomic relevance

Method	What it measured	OSH relevance
OWAS observation	Frequency of non-neutral postures during active work	Identifies cumulative exposure to neck, shoulder and upper-limb load
Process-flow recording	Work sequence, non-value-added movement and operation time	Shows whether exposure is caused by avoidable layout losses
5S audit	Sorting, organization, cleaning, standardization and discipline	Prevents return to clutter and improvised work
Hierarchy of controls	Strength of controls relative to the source of risk	Prioritizes engineering and organizational measures over behaviour alone

4. PRE-REDESIGN WORKSTATION ERGONOMIC ASSESSMENT

The baseline workstation did not present one dominant acute hazard. Instead, the main risk developed through cumulative ergonomic exposure associated with repetitive assembly work.The worker adapted to a fixed work height, scattered material supply and unsupported tool handling. The observed exposure was mainly associated with repetitive fastening, component positioning and visual inspection during terminal-box or cover subassembly.

The two most important ergonomic indicators were elevated upper-arm posture and forward head inclination. Elevated arm posture was observed during 60% of active working time, mainly during repetitive tool use. Forward-inclined head posture was present during 57% of observed working time and reached a critical action level. Figure 2 illustrates the underlying ergonomic problem: poor workstation design transformed repetitive precision assembly into sustained neck and shoulder loading.

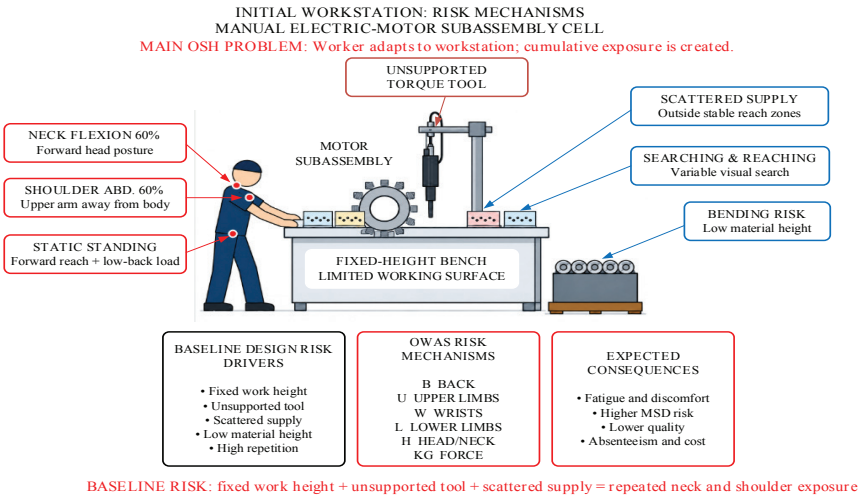


Figure 2: Ergonomic risk mechanisms before workstation redesign

5. WORKSTATION REDESIGN

The workstation redesign included a height-adjustable work surface, locating fixture, integrated lighting, suspended torque screwdriver with balancer, organized reach zones and standardized material supply. These measures reduced unnecessary reaching, unsupported tool handling and visually driven neck flexion during repetitive assembly work. The redesigned workstation concept is presented in Figure 3.

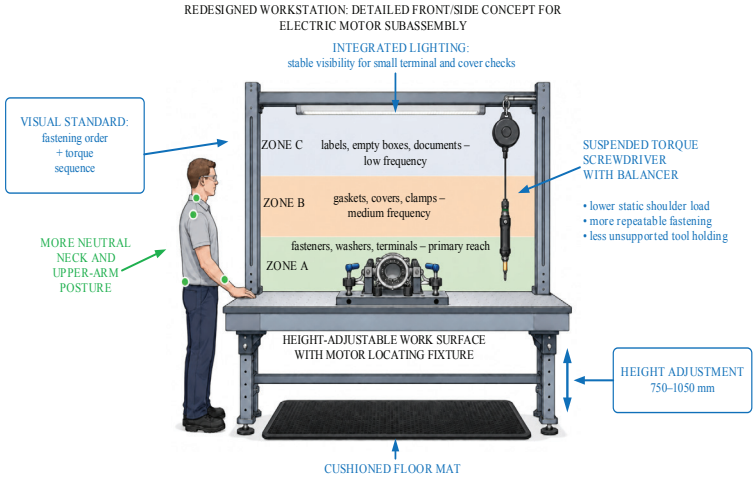


Figure 3: Redesigned electric-motor subassembly workstation shown in front view.

The redesign combines engineering and organizational controls. Improved work height reduces the need for neck flexion, the balancer reduces static shoulder load, the fixture stabilizes the subassembly, and reach-zone organization reduces unnecessary searching, reaching and bending. Table 3 summarizes the ergonomic purpose of each redesign measure.

Table 3: Redesign measures and their ergonomic purpose

Redesign measure	Control type	Preventive safety function
Height-adjustable work surface	Engineering	Adapts work height to worker and task; reduces neck flexion
Locating fixture	Engineering	Stabilizes the subassembly and reduces awkward repositioning
Suspended torque screwdriver	Engineering	Reduces tool-weight load and upper-arm abduction
Integrated lighting	Engineering	Improves visibility and reduces visual-driven head flexion
Reach zones and kanban trolley	Organizational / engineering	Places frequent components close and stabilizes material supply
5S visual standard	Administrative / organizational	Maintains order and supports periodic audit discipline

6. RESULTS

The redesigned workstation reduced both posture exposure and unnecessary movement during manual assembly work. Elevated upper-arm posture decreased from 60% to 46%, while forward-inclined head posture decreased from 57% to 39%. The head/neck exposure category improved from a critical action level to a lower monitoring level. Figure 4 summarizes the posture-related outcomes together with the operation-time result.

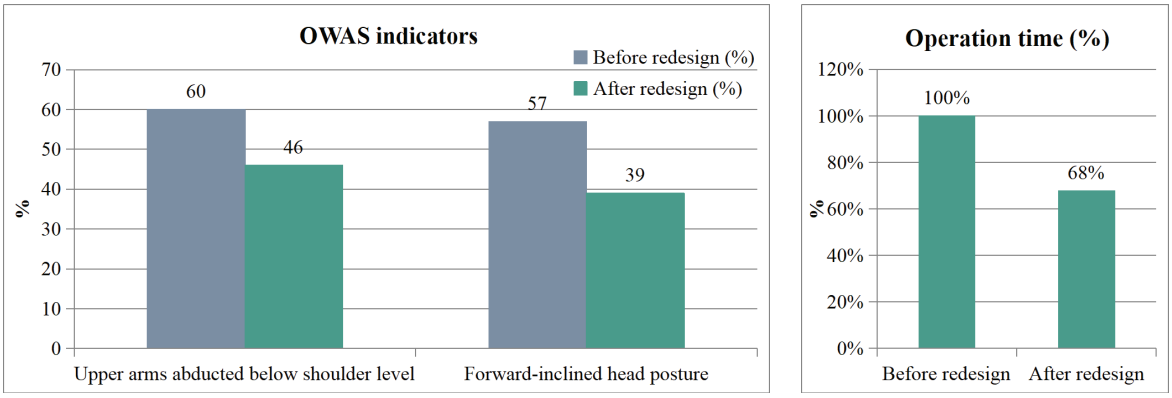


Figure 4: Before-and-after outcomes for OWAS posture indicators and operation time.

Operation time decreased from 5 minutes 23 seconds to 4 minutes 15 seconds. The shorter cycle primarily resulted from reduced searching, unnecessary reaching and unsupported tool handling rather than from increased work pace. Table 4 summarizes the measured outcomes and their ergonomic interpretation.

Table 4: Key ergonomic and operational indicators before and after workstation redesign

Indicator	Before redesign	After redesign	Change	OSH interpretation
Upper arms abducted below shoulder level	60%	46%	-14 pp	Reduced shoulder exposure during repeated fastening
Forward-inclined head posture	57%	39%	-18 pp	Critical neck exposure reduced to lower action level
5S workplace audit	Not stabilized	23/25 points	92%	Workplace order became visible and auditable
Operation time	5:23	4:15	-1:08	Cycle shortened through safer design, not higher effort

7. DISCUSSION

The case demonstrates that workstation redesign can reduce cumulative ergonomic load in manual electric motor assembly. The main problem was not an isolated unsafe action, but a workstation layout that required repeated neck flexion, unsupported tool handling and unnecessary searching for parts during assembly work. Such conditions are common in mixed-model production environments with changing product variants, component combinations and time pressure.

The reduction in forward head inclination was particularly important because terminal connection, cover alignment and visual inspection require high visual precision. When the work surface is too low or poorly illuminated, workers naturally lean forward to bring the eyes closer to the task. The observed reduction therefore indicates that workstation height, lighting and component positioning improved working posture during assembly. The reduction in elevated arm posture also indicates lower shoulder loading, although some residual exposure remains unavoidable in manual fastening and positioning operations.

The electric motor assembly context also highlights the connection between ergonomic conditions and assembly consistency. Stable fixture positioning, organized material supply and supported tool handling can reduce operator fatigue while improving fastening repeatability and visual inspection reliability. Ergonomic workstation design therefore contributes not only to worker well-being, but also to process stability and assembly quality [4,8,11].

Similar manual assembly workstations should include repetitive fastening, visual inspection and line-side material handling in formal ergonomic assessment procedures. Height-adjustable work surfaces and fixtures can reduce neck flexion during positioning and inspection tasks, while suspended torque tools reduce static shoulder loading during repetitive fastening. Frequently used components should remain within optimized reach zones, and workplace organization measures such as 5S should support ergonomic consistency rather than housekeeping alone. Operation-time improvements should always be interpreted together with posture exposure and worker feedback to ensure that reduced cycle time results from improved workflow rather than increased physical effort.

The redesigned workstation should not be treated as a one-time technical improvement, but as a working condition that must remain stable during daily production. This is particularly important in electric motor assembly, where product variants, fastening sequences, terminal layouts and component kits may change over time. A workstation that initially provides acceptable ergonomic conditions can gradually deteriorate if additional material is placed on the work surface, if tool balancing is removed or if lighting and material supply are no longer maintained consistently. For this reason, long-term ergonomic control should be considered part of the redesign process itself.

For this reason, workstation follow-up should include both condition-based and outcome-based indicators. Condition-based indicators verify whether the redesigned workstation arrangement is still maintained in practice, including tool balancing, fixture position, reach-zone organization and material replenishment. Outcome-based indicators reflect whether the workstation remains acceptable during production, including posture exposure, worker discomfort, rework and cycle-time trends. Evaluating these indicators together helps determine whether the observed improvement results from better workstation organization or from increased physical strain on the worker.

Table 5 presents a practical follow-up plan for maintaining acceptable ergonomic conditions at the redesigned workstation. The proposed approach is intentionally simple so that it can be applied in SMEs without complex digital infrastructure. At the same time, the approach remains compatible with more advanced ergonomic monitoring methods, including digital work instructions or camera-based posture assessment systems.

Table 5: Follow-up plan for maintaining the redesigned workstation conditions

Follow-up area	Control indicator	Recommended frequency	Corrective action if drift is detected
Posture exposure	OWAS or simplified posture check for head/neck and upper arms	after layout change and periodically	review work height, fixture position, lighting and tool angle
Tool support	torque screwdriver remains suspended and balanced	daily visual check	adjust balancer, cable routing and tool-rest position
Reach-zone discipline	frequent components remain in Zone A/B; no unnecessary boxes on the surface	weekly 5S review	rearrange bins, update visual standard and retrain material supply
Material flow	empty-bin / kanban cards returned without delay	weekly or after product variant change	correct replenishment route and reduce emergency picking
Worker feedback	reported discomfort, fatigue, awkward reach or visibility issue	monthly OSH review	include operator feedback in corrective-action log
Process stability	cycle time, rework and repeated corrections	monthly or after engineering change	verify that time reduction is not achieved by increased pace

The main value of the follow-up approach is that it supports early correction before discomfort, absenteeism or repeated ergonomic overload become visible problems. Small deviations in workstation organization or tool support can usually be corrected quickly, whereas unmonitored deterioration may gradually return the workstation to the original high-exposure condition.

The proposed approach is also transferable to similar manual assembly environments. Even when products, dimensions and layouts differ, the same general sequence can be applied: identify cumulative ergonomic exposure, redesign the workstation using engineering and organizational measures, verify the resulting posture conditions and maintain the improvements through periodic follow-up.

The main limitation of the study is that it represents a single-workstation case. The results are therefore directly transferable only to similar manual assembly operations and should be validated locally for different motor sizes, component weights, takt times, torque requirements and worker anthropometry. OWAS provides a robust observational basis for posture assessment, but it does not directly measure muscle activation, joint loading or long-term health outcomes. Future work could include discomfort questionnaires, electromyography, computer-vision posture monitoring, torque-quality analysis and longer follow-up periods.

8. CONCLUSION

The presented case shows that ergonomic workstation redesign can reduce cumulative physical load in manual electric motor assembly. Elevated upper-arm posture decreased from 60% to 46%, while forward head inclination decreased from 57% to 39%. The redesigned workstation achieved a 5S audit result of 23/25 points, and operation time decreased from 5:23 to 4:15. The observed improvements were primarily associated with reduced unnecessary reaching, unsupported tool handling and visually driven neck flexion. The case demonstrates that ergonomically designed manual assembly workstations can support worker well-being while improving process stability and assembly consistency.

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Professional paper

ARTIFICIAL INTELLIGENCE AND PSYCHOSOCIAL RISKS IN THE WORKPLACE: A SURVEY-BASED CASE STUDY AT A PORTUGUESE PORT AUTHORITY

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Abstract: *Artificial Intelligence (AI) is reshaping work processes and introducing new psychosocial risks that remain insufficiently addressed by current occupational safety and health frameworks. This paper presents the results of a survey-based case study conducted among employees of a Portuguese port authority (Administração do Porto de Sines), aiming to characterise workers' perceptions of AI-related psychosocial risks and the role of training and regulation in mitigating them. An online questionnaire was distributed to 186 employees, yielding 33 valid responses (17.75%). Results show that only 30.3% of respondents perceive clear advantages from AI adoption, while 69.7% report concerns about its impact on mental and emotional health, particularly job insecurity, information overload and stress. Although 90.9% consider training essential to cope with AI-driven change, current training and psychosocial support are perceived as insufficient. Findings underline the urgency of integrating AI-specific psychosocial risk assessment into occupational safety and health management systems.*

Keywords: *Artificial Intelligence; Psychosocial Risks; Occupational Safety and Health; Technostress; Digital Transformation*

1. INTRODUCTION

Artificial Intelligence (AI) is increasingly embedded in organisational processes, redefining how tasks are performed, monitored and evaluated. While AI adoption promises efficiency gains and improved decision-making, it also introduces new sources of psychosocial risk that traditional occupational safety and health (OSH) frameworks were not originally designed to capture. Job insecurity, algorithmic surveillance, information overload and the erosion of worker autonomy are among the concerns increasingly reported in technologically intensive work environments.

Despite growing academic and regulatory attention to these issues, empirical evidence on how workers themselves perceive AI-related psychosocial risks remains limited, particularly within Portuguese organisations. This paper addresses that gap by presenting findings from a survey-based case study conducted among employees of Administração do Porto de Sines (APS), a Portuguese port authority.

The study pursued three objectives: (i) to characterise workers' perceptions of the advantages associated with AI adoption in the workplace; (ii) to identify the psychosocial risks most frequently associated with AI implementation; and (iii) to examine the extent to which regulation and training are perceived as effective means of mitigating these risks. These objectives were operationalized through three research questions, which structure the results and discussion presented in Section 4.

The remainder of the paper is organized as follows. Section 2 reviews the theoretical background on AI as a social and organisational phenomenon and the psychosocial risks associated with its adoption. Section 3 describes the methodology, including the case organization, sample and data collection instrument. Section 4 presents and discusses the results. Section 5 concludes with the main contributions, limitations and directions for future research.

2. THEORETICAL BACKGROUND

2.1. Artificial Intelligence as a Social and Organisational Phenomenon

AI is not merely a technical innovation; it is a complex social phenomenon that reshapes organisational structures and labour markets. Its adoption has produced more flexible, but often more precarious, employment models, while simultaneously demanding advanced technical qualifications from workers.

These transformations result from the interaction between technology, economy and society, and their effects on occupational safety and health are only beginning to be systematically studied [14].

2.2. Key Concepts

Several concepts underpin the analysis of AI's effects on work. Automation refers to the total or partial replacement of human tasks by automated systems. Digital transformation denotes the integration of digital technologies to increase operational efficiency [12]. Technostress describes the anxiety, fatigue and sense of inadequacy generated by the pressure to continuously adapt to evolving technologies [13]. Flexible work, enabled by AI, allows remote work and flexible schedules, but simultaneously challenges established labour rights and safety guarantees.

2.3. Psychosocial Risks Associated with AI

The literature identifies a broad set of psychosocial risks linked to AI adoption in the workplace, which can be grouped into three main clusters. The first concerns individual health and well-being, including technostress, exhaustion and burnout resulting from excessive technology use and social isolation, together with dependency-related effects such as reduced creativity and disrupted sleep patterns. The second cluster relates to organisational dynamics, encompassing job insecurity driven by algorithmic monitoring and decision-making, work overload, and threats to work–life balance [11]. The third cluster concerns societal and ethical dimensions, including data-driven discrimination,

erosion of privacy, and broader concerns about manipulation and disinformation. Public figures have expressed sharply divergent views on the scale of these risks: while some technology leaders emphasize AI's largely positive and transformative potential, other scientists have warned of the existential risks associated with insufficiently controlled AI systems.

2.4. The Role of Regulation and Training

Regulatory frameworks, such as the European Union's Artificial Intelligence Act, are considered essential to protect workers' rights and well-being in the face of automation. Alongside regulation, continuous training and clear communication are regarded as critical levers for reducing psychosocial risk, as they increase workers' sense of control and competence when interacting with AI-driven systems [2]. It is also useful to distinguish between risk and risk factors in this context: risk refers to the potential for harm — physical, psychological or social — to the individual (e.g., stress, harassment, discrimination), whereas risk factors originate in planning, structuring or management failures that increase that risk (e.g., poorly defined tasks, lack of guidance, excessive workload, insufficient feedback).

3. METHODOLOGY

This study adopted a case study approach, focused on Administração do Porto de Sines (APS), a Portuguese public port authority. Data were collected through an online questionnaire distributed by the organization's Human Resources department to its workforce. Of the 186 employees invited to participate (131 men and 55 women), 33 valid responses were obtained, corresponding to a response rate of 17.75%.

The questionnaire was designed to investigate workers' perceptions across three dimensions, aligned with the study's research questions: perceived advantages of AI in the workplace, psychosocial risks associated with its implementation, and the perceived adequacy of training and regulatory support [4]. Item development was informed by a systematic review of the literature on automation, technostress, the socioeconomic impact of AI, and relevant legislation.

Given the relatively small sample size and the exploratory nature of the study, data were analyzed using descriptive statistics. Results are presented as percentages of respondents per item and discussed in light of the relevant literature in the following section.

4. RESULTS AND DISCUSSION

Table 1 summarizes the main quantitative findings from the survey, organized according to the study's three research questions.

Table 1: Summary of key survey results

Indicator	Result
Respondents perceiving a clear advantage from AI	30.3%
Respondents perceiving no advantage from AI	9.1%

Indicator	Result
Respondents reporting negative impact on mental/emotional health	69.7%
Respondents considering training important to face AI-driven change	90.9%
Respondents considering training “very important”	69.7%

4.1. Perceived Advantages of AI in the Workplace

Findings indicate that perceptions of AI’s advantages remain limited: only 30.3% of respondents identified clear benefits, mostly related to increased speed, quality and efficiency, while 9.1% reported no perceived advantage whatsoever. This is broadly consistent with the literature, which associates AI adoption with productivity gains, improved daily efficiency, reduced repetitive workload and better-informed decision-making [1]. However, the relatively low proportion of respondents endorsing these benefits suggests a gap between the advantages documented in the literature and workers’ lived experience, indicating that potential gains are not yet being fully realized — or effectively communicated — at the operational level [4].

4.2. Psychosocial Risks Associated with AI Implementation

A substantial majority of respondents (69.7%) reported that AI can disrupt workers’ mental and emotional health, citing job insecurity, information overload, loss of control and stress as principal concerns. This finding aligns with the literature identifying AI as a significant contributor to the emergence of burnout, stress and anxiety in technologically intensive work environments [9]. It also corroborates prior evidence that workers’ fears about task displacement are closely tied to concerns over job security, reinforcing the relevance of psychosocial risk assessment frameworks that explicitly account for AI-specific stressors, such as reduced worker autonomy [10].

4.3. The Role of Regulation and Training

While 90.9% of respondents agreed that investment in training is important to prepare for AI-driven change (69.7% considering it “very important”), a large majority also reported that current training provision at APS is perceived as insufficient, and that adequate psychosocial support to deal with AI-related risks is largely absent. This is consistent with the literature emphasizing that insufficient or inadequate training can generate anxiety, uncertainty and diminished confidence in technology use [2], and that continuous training reduces workers’ apprehension while increasing their adaptive capacity. The gap between the perceived importance of training and its actual availability at APS points to a broader disparity — also noted in the literature — between the psychosocial support policies organisations should implement and those genuinely available to workers facing AI-driven change.

5. CONCLUSION

This study examined how AI adoption is perceived by workers of a Portuguese port authority, focusing on associated psychosocial risks and the role of training and regulation in mitigating them. The study’s objectives were only partially achieved: while the survey provided valuable insight into workers’ concerns, a considerable proportion of neutral or non-committal responses — particularly regarding less familiar concepts such as coping strategies and technostress — limited the depth of the conclusions that could be drawn [5].

The findings nonetheless make a relevant contribution by highlighting persistent gaps in AI-related training, the absence of structured psychosocial support mechanisms, and the corresponding need for clearer regulatory guidance. Workers demonstrated a dual perception of AI: concern regarding stress, pressure and the risk of task displacement, alongside recognition of its potential to improve efficiency, productivity and create new opportunities.

The main limitations of this study include the relatively low response rate, the early stage of AI adoption within the case organization — which constrained respondents' ability to evaluate its practical benefits — and the resulting prevalence of neutral responses. Future research should further examine the boundaries of acceptable AI use in occupational contexts, its emotional impact on workers, and the ethical risks associated with its implementation, ideally through longitudinal designs capable of tracking these perceptions as AI adoption matures.

Ultimately, this study reinforces the importance of balancing technological innovation with respect for workers' rights, ensuring that AI is designed and implemented to support — rather than replace — the human dimension of work.

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Original scientific paper

APPLICATION OF ANTHROPOMETRIC MEASUREMENTS IN THE DEVELOPMENT OF PROTECTIVE CLOTHING SIZING SYSTEMS FOR THE IMPROVEMENT OF OCCUPATIONAL SAFETY

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Abstract: *Protective clothing plays an important role in preserving workers' health and safety, as it must provide adequate protection, comfort, and freedom of movement during work activities. Existing sizing systems are most commonly based on main body measurements, such as body height and chest circumference, which are often insufficient to ensure proper fit of protective clothing for different users. Inappropriate sizing may cause reduced mobility, discomfort, and an increased risk of occupational injuries.*

The aim of this paper is to present the importance of applying additional anthropometric measurements in the development of a modern sizing system for protective clothing. The analysis is based on anthropometric measurements conducted on the male population in the Republic of Croatia. In addition to the basic control dimensions, additional measurements were observed, such as waist circumference, hip circumference, upper arm circumference, upper and mid-thigh circumference, and length measurements important for garment construction. By introducing additional anthropometric variables, it is possible to develop more precise patterns for protective clothing, improve ergonomic adaptation to the user, and reduce movement restrictions during work. This increases worker safety, work efficiency, and satisfies the fit requirements of protective clothing.

Keywords: *anthropometry, protective clothing, occupational safety, ergonomics, clothing sizing system, worker safety*

1. INTRODUCTION

Protective clothing represents an important part of personal protective equipment whose primary purpose is to protect workers from various hazards and harmful influences during work activities. In many industrial sectors, workers are daily exposed to mechanical, thermal, chemical, and other hazards that may endanger their health and safety. When risks cannot be completely eliminated through technical or organizational measures, the use of appropriate protective clothing becomes necessary. Such clothing must ensure the required level of protection, comfort, and functionality.

Modern protective clothing must also satisfy the ergonomic requirements of users. Clothing should allow freedom of movement, comfort during work, and adaptation to different working positions and activities. Improper fit of protective clothing may cause discomfort, restricted movement, increased physical strain on workers, and reduced work efficiency. According to the requirements of the HRN EN 340 standard, protective clothing must be designed to follow the static and dynamic morphology of the human body and enable unobstructed movement during work activities [1]. Protective clothing sizes are defined based on basic body measurements such as body height and chest circumference, with the possibility of applying additional measurements such as sleeve length or trouser length. However, existing sizing systems are most often based on a limited number of basic anthropometric measurements, which is frequently insufficient for proper adaptation to different body types of users. Anthropometry, as a scientific discipline, studies the dimensions and proportions of the human body and plays an important role in the development of ergonomic products and clothing systems. By applying additional anthropometric measurements, it is possible to develop more precise sizing systems that ensure better fit, greater comfort, and improved safety at work [2–4].

Recent studies have increasingly highlighted the importance of advanced anthropometric databases, 3D body scanning technologies and digital sizing systems for improving the ergonomic performance of protective clothing. Although international standards remain the basis for clothing size designation, recent research indicates that multidimensional anthropometric variables provide significantly better garment fit and user comfort, particularly in occupational environments requiring unrestricted movement. Therefore, the present study focuses on the application of additional anthropometric measurements for improving protective clothing sizing systems.

2. EXPERIMENTAL PART

In accordance with the ISO 8559 and EN 13402-3:2017 standards, a study was conducted on a sample of 189 male subjects aged between 22 and 35 years [5,6]. Anthropometric measurements were carried out using the conventional measurement method. In addition to the basic body measurements, additional anthropometric measurements important for the construction of protective clothing were also analyzed [7]. The anthropometric dataset analysed in this paper originates from measurements previously conducted within the first author's doctoral research (Reference [8]). In the present paper, these data are re-analysed from a different perspective, with emphasis on their application in the development of protective clothing sizing systems for occupational safety. Measurements were performed according to ISO 8559-1 and EN 13402-3 using conventional anthropometric procedures by trained personnel.

3. RESULTS AND DISCUSSION

The results presented in Table 1 show a certain variability of anthropometric measurements within the examined population. The average body height of the subjects was 180.1 cm, with a relatively low coefficient of variation of 3.3%, indicating lower data dispersion. On the other hand, significantly greater deviations were recorded for circumference measurements. The highest coefficient of variation was determined for upper arm circumference (12.9%) and waist circumference (12.6%), indicating pronounced differences in the body build of the subjects. The obtained results confirm that sizing systems based solely on body height and chest circumference cannot ensure an optimal fit of protective clothing for all users.

Beyond descriptive statistics, the results indicate that body circumferences exhibit substantially

greater variability than body height, suggesting that traditional sizing systems based solely on body height and chest circumference may not adequately accommodate the diversity of body shapes. This represents the principal scientific contribution of this study by identifying additional anthropometric variables that should be considered when designing protective clothing for the Croatian male population.

Additional anthropometric measurements such as upper arm circumference, mid-thigh circumference, sleeve length, and trouser length play an important role in the construction of protective clothing because they directly influence freedom of movement and ergonomic adaptation to the user. Incorrectly determined sleeve and trouser leg dimensions may cause material tension, restricted movement, and reduced functionality of the clothing system during work activities [8].

Table 1. Descriptive statistics of basic and additional anthropometric measurements of the subjects

Body Measurement (cm)	Mean ($\bar{x}$)	s	CV (%)	95% CI	Min.	Max.
Body Height	180.1	6.02	3.3	179.2 – 180.9	170.0	200.5
Chest Circumference	92.5	9.03	9.8	91.2 – 93.8	72.7	131.0
Waist Circumference	81.9	10.36	12.6	80.4 – 83.3	61.0	130.0
Hip Circumference	99.1	7.96	8.0	98.0 – 100.3	82.0	135.0
Upper Arm Circumference	30.2	3.90	12.9	29.6 – 30.7	22.5	45.0
Right Sleeve Length	64.4	4.06	6.3	63.8 – 65.0	52.0	77.0
Mid-Thigh Circumference	47.2	5.59	11.8	46.4 – 48.0	33.0	66.0
Pants Length	111.1	5.58	5.0	110.3 – 111.9	95.0	126.0

Table 1 presents the basic and additional anthropometric measurements of the subjects that were analyzed with the aim of determining their importance in the development of a sizing system for protective clothing. Arithmetic means, standard deviations, coefficients of variation, confidence intervals, and minimum and maximum values of individual measurements are presented. The results show that the average body height of the subjects was 180.1 cm, with a relatively low coefficient of variation of 3.3%, indicating lower data dispersion within the observed population. On the other hand, significantly greater deviations were recorded for circumference measurements. The highest coefficient of variation was determined for upper arm circumference (12.9%) and waist circumference (12.6%), indicating pronounced differences in the body build of the subjects. Chest circumference showed an average value of 92.5 cm, while the average hip circumference was 99.1 cm. The range between the minimum and maximum values of these measurements indicates considerable population heterogeneity, confirming that sizing systems based solely on basic control dimensions cannot ensure an optimal fit of protective clothing for all users.

The analysis of additional anthropometric measurements determined the importance of measurements that directly influence the construction and ergonomic adaptation of protective clothing. The average upper arm circumference was 30.2 cm, while the average mid-thigh circumference was 47.2 cm. These measurements play an important role in the design of sleeves and trouser legs of protective clothing in order to ensure freedom of movement during work activities. The average right sleeve length was 64.4 cm, while the average trouser length was 111.1 cm. The range of values of these length measurements indicates the need to adapt constructional elements of protective

clothing to different body proportions of users. Incorrectly determined sleeve and trouser leg lengths may result in reduced clothing functionality, restricted movement, and a lower level of protection for certain body parts during work activities. The obtained results confirm the importance of applying additional anthropometric measurements in the development of a modern sizing system for protective clothing. By including a larger number of body measurements, it is possible to develop more precise construction models that ensure better ergonomic adaptation, greater user comfort, and improved safety during work activities. The coefficient of variation graph presents the degree of variability of individual anthropometric measurements within the examined population. The highest coefficients of variation were recorded for upper arm circumference (12.9%), waist circumference (12.6%), and mid-thigh circumference (11.8%), indicating significant differences in the body build of the subjects. On the other hand, body height showed the lowest variability (3.3%), confirming that body height alone is not sufficient for determining the optimal size of protective clothing. The obtained results confirm the need to include additional anthropometric measurements in the development of modern sizing systems for protective clothing in order to ensure better ergonomic adaptation for users, Figure 1.

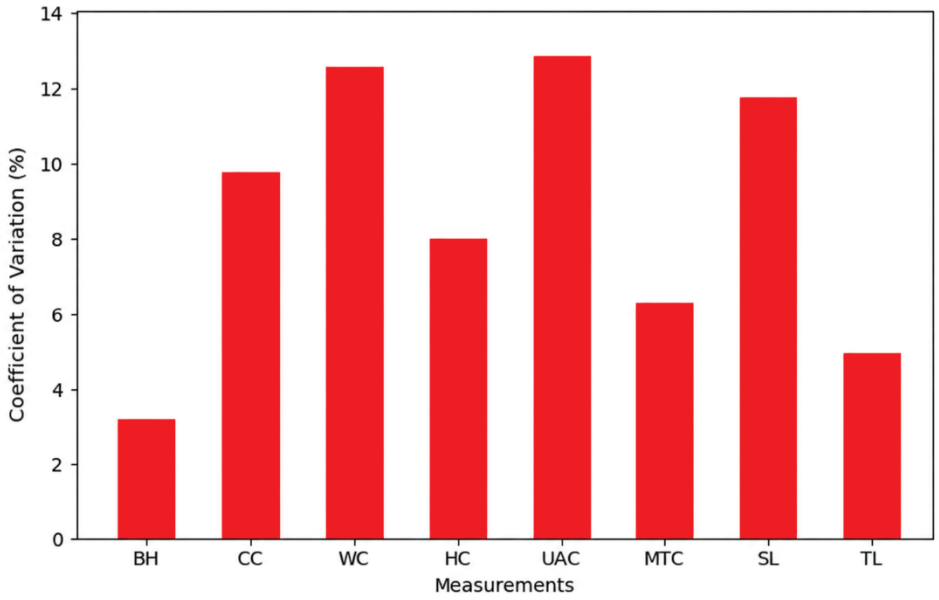


Figure 1. Coefficient of variation of anthropometric measurements

The graph of average anthropometric measurement values presents the average dimensions of the examined population for the basic and additional body measurements important in the construction of protective clothing. The highest average values were recorded for body height and trouser length, while lower values were observed for upper arm circumference and mid-thigh circumference. The analysis of average values enables the definition of basic construction parameters for the development of a sizing system for protective clothing. However, average values alone are not sufficient for proper clothing adaptation to all users due to pronounced individual differences among the subjects. Therefore, when constructing protective clothing, it is also necessary to take into account the range of deviations of individual anthropometric measurements, Figure 2.

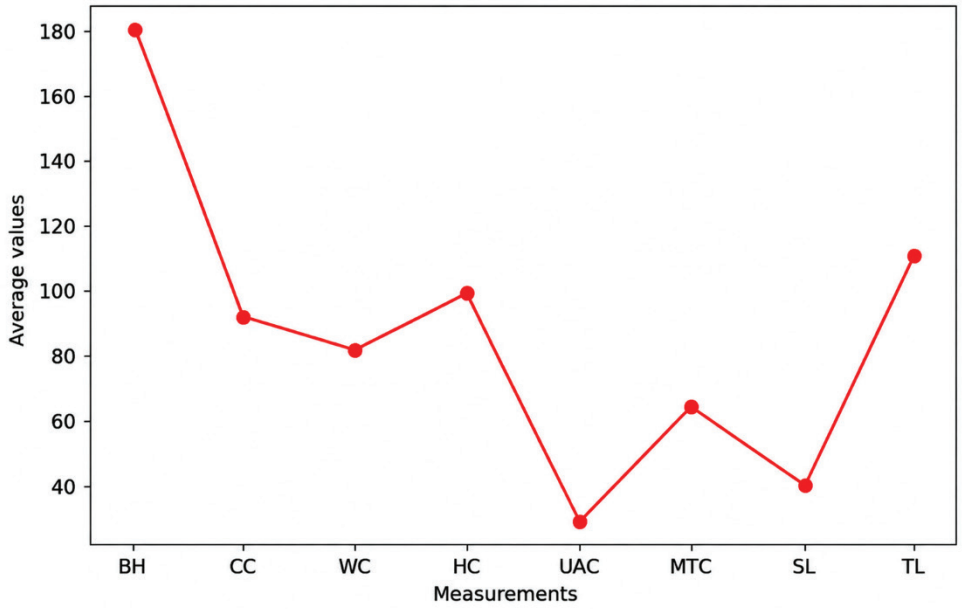


Figure 2. Average values of anthropometric measurements

Based on the obtained results, it can be concluded that the development of a modern sizing system for protective clothing requires the application of a multidimensional approach which, in addition to basic control dimensions, also includes additional anthropometric variables. It is proposed that the sizing system, alongside body height and chest circumference, should also include: waist circumference, hip circumference, upper arm circumference, mid-thigh circumference, sleeve length, and trouser length. By introducing additional anthropometric measurements, it is possible to develop more precise construction models of protective clothing that will enable a better fit for different body types and increase comfort and safety during work activities.

4. CONCLUSION

The research results showed that there are significant differences in the anthropometric characteristics of the subjects, especially in measurements that are not included in traditional sizing systems for protective clothing. The obtained results confirm that basic control dimensions are not sufficient for optimal ergonomic adaptation of protective clothing to different users. Based on the analysed anthropometric data, it may be concluded that incorporating additional body dimensions into protective clothing sizing systems could improve ergonomic fit and may contribute to greater comfort and potentially improved occupational safety. Nevertheless, further studies involving wear trials, functional ergonomic testing and 3D body scanning are recommended to validate these findings in practical working environments.

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Original scientific paper

PSYCHOSOCIAL RISKS AMONG WORKERS IN THE TEXTILE INDUSTRY

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Abstract: *Psychosocial risks at work are an important factor in preserving employees' mental and physical health, particularly in industries characterised by repetitive tasks, time pressure, and limited autonomy. The aim of this study was to examine the presence and characteristics of psychosocial risks among workers employed in the textile industry. The study included 62 workers, and the Psychosocial Risk Questionnaire was used to assess sources of work-related stress, perceived job insecurity, the subjectively most prominent source of stress, and the consequences of exposure to work-related stress. Among the assessed psychosocial risk domains, limited job control showed the highest risk level, indicating workers' reduced ability to make decisions about important aspects of their work. These findings indicate the need for preventive measures aimed at improving work organisation, strengthening employee support, and increasing worker autonomy.*

Keywords: *psychosocial risks, work-related stress, job control, textile industry*

1. INTRODUCTION

Work-related stress is becoming an increasingly important risk to workers' mental and physical health. Faster production processes, increasing work complexity, new technologies, constant availability, and job insecurity are among the factors contributing to increased psychosocial risks in the workplace [1].

One of the fundamental definitions of stress was proposed by Lazarus, according to whom stress occurs when there is an imbalance between environmental demands and an individual's ability to respond to those demands [2]. Psychosocial stressors in the workplace arise from an imbalance

between job demands, the work environment, work content and organisation, on the one hand, and workers' physical and psychological characteristics, needs, and competencies, on the other [3].

Research has shown that prolonged exposure to psychosocial risks increases the likelihood of developing mental health disorders, such as anxiety, depression, and burnout, as well as certain physical health conditions, including cardiovascular and musculoskeletal disorders. These effects may also have consequences for work performance and broader societal costs [1].

Consequently, recent approaches increasingly emphasise the development of "healthy organisations" and workplace cultures that support workers' mental health, for example through reasonable job demands, adequate support from supervisors and co-workers, and greater autonomy in performing work tasks [4].

The Occupational Safety Act (Official Gazette No. 71/14) stipulates employers' obligations regarding the prevention of work-related stress [5], while the Ordinance on Risk Assessment (Official Gazette No. 112/14) identifies psychophysical workload as a mandatory component of occupational risk assessment [6].

The Ordinance on Occupational Safety for Workers Exposed to Static-Dynamic, Psychophysiological and Other Workloads (Official Gazette No. 73/2021) [7] distinguishes between psychosocial risks and psychophysiological workload arising from exposure to psychosocial risks in the workplace. Psychosocial risks are classified into nine groups: work content, degree of job control, mental workload, social environment and interpersonal relationships, time management and work allocation, job insecurity, respect for personal integrity, work-life balance, and working-environment conditions such as lighting, noise, and vibration.

The aim of this study was to examine the presence of psychosocial risks among workers employed in the textile industry.

2. METHODS

2.1. Procedure

The study was conducted from 8 to 19 July 2024 in two textile companies engaged in garment manufacturing in Karlovac County. Printed questionnaires were distributed to sewing workers in each company and completed during their work breaks. Participation was anonymous. The study was conducted as part of a broader research project, TeksErgo: Ergonomic Aspects and the Development of Safety Culture in the Textile Industry.

2.2. Participants

The study included 62 sewing workers employed in the two participating companies. Of these, 3 (5%) were male, 54 (87%) were female, and 5 (8%) did not respond to this question. Most participants (76%) were aged 46 years or older, while 32% of the total sample were older than 55 years. Regarding education, 77% had completed secondary education, 15% had completed primary education, and 8% did not report their educational level.

2.3. Instrument

Psychosocial risks were assessed using the Psychosocial Risk Questionnaire [8]. The questionnaire is available from the Croatian Institute of Public Health, Occupational Health Service. It was adapted for occupational risk assessment in accordance with national legislation and is based on the Management Standards Indicator Tool [9], whose seven-factor structure has been confirmed in previous research [10]. The questionnaire assesses:

- sources of work-related stress;
- perceived job insecurity;
- the subjectively most prominent source of stress; and
- experienced consequences of exposure to work-related stress.

Sources of work-related stress are grouped into seven categories: job demands, interpersonal relationships, job control, lack of supervisor support, lack of co-worker support, role, and lack of information about organisational changes. Each category consists of three to eight items. Participants rated the extent to which each item applied to their work on a five-point scale ranging from 1 (never) to 5 (always).

Perceived job insecurity is assessed as a separate risk measure using a four-item scale. Participants responded on a five-point scale ranging from 1 (strongly disagree) to 5 (strongly agree).

The subjectively most prominent source of stress is assessed using the following open-ended question: “What represents the greatest source of stress for you at work?”

Experienced consequences of exposure to work-related stress are grouped into three categories (A, B, and C). Category A refers to reduced work performance and brief episodes of distress accompanied by stress reactions. Category B refers to prolonged periods of reduced work performance, frequent physical, cognitive, and emotional symptoms of stress, and short-term sick leave. Category C refers to stress-related health problems, chronic fatigue, prolonged sick leave, continuously reduced work performance, and work avoidance. Participants selected the category that best described their experience.

Demographic questions covered sex, age, and educational level.

3. RESULTS AND DISCUSSION

The results were interpreted according to the Guidelines for the Interpretation of the Psychosocial Risk Assessment Questionnaire [11].

3.1. Sources of Work-Related Stress

Mean scores were calculated for each category of work-related stress. The results are presented in Table 1. The highest risk level was observed in the job control domain (M = 3.8, SD = 0.16), while the lowest was observed for role (M = 1.2, SD = 0.10). The overall mean score was 2.4 (SD = 1.31).

According to the interpretation guidelines, the mean score for job control corresponds to an elevated stress level, while the mean score for role corresponds to a low stress level. Scores for the remaining categories indicate a moderate stress level.

Table 1: Mean scores for the seven categories of work-related stress

Category of work-related stress	Mean	Standard deviation	Stress level
Job control	3.8	0.16	Elevated
Job demands	2.6	0.16	Moderate
Lack of information about organisational changes	2.4	0.11	Moderate
Lack of co-worker support	2.3	0.07	Moderate
Interpersonal relationships	2.2	0.16	Moderate
Lack of supervisor support	2.1	0.20	Moderate
Role	1.2	0.10	Low
Overall mean score	2.4	1.31	-

The obtained score also represents a measure of the likelihood of exposure to psychosocial risks in the workplace, in accordance with the Ordinance on Risk Assessment (Official Gazette No. 112/14). According to the Ordinance, risk assessment is carried out using a risk assessment matrix, with risk classified as low, medium, or high. The Guidelines for the Interpretation of the Psychosocial Risk Assessment Questionnaire [11] define the likelihood of exposure to psychosocial risks in the workplace as follows:

- unlikely: mean score < 3
- likely: mean score between 3 and 4
- very likely: mean score ≥ 4

Based on these criteria, Table 2 presents the likelihood of exposure to psychosocial risks for each category of work-related stress.

Table 2: Likelihood of exposure to psychosocial risks

Work-related stressor category	Criterion	Likelihood of exposure
Job demands	Mean score < 3	Unlikely
Interpersonal relationships	Mean score < 3	Unlikely
Lack of supervisor support	Mean score < 3	Unlikely
Lack of co-worker support	Mean score < 3	Unlikely
Role	Mean score < 3	Unlikely
Lack of information about organisational changes	Mean score < 3	Unlikely
Lack of job control	Mean score between 3 and 4	Likely
None of the assessed categories	Mean score ≥ 4	Very likely

Accordingly, lack of job control was the only category indicating a likely exposure to psychosocial risks, while all other assessed categories were classified as unlikely.

Job control refers to workers' ability to make decisions about aspects of their work, such as work pace, the timing of rest breaks, the way tasks are performed, and flexibility in working hours. Autonomy is recognised as one of the components of psychological well-being [12]. A study conducted in the garment industry found that autonomy at work and participation in decision-making were significantly associated with occupational stress among workers [13].

3.2. Perceived Job Insecurity

The mean score on the job insecurity scale was 2.6 (SD = 0.10). According to the interpretation guidelines, a mean score of 2.6 indicates a low likelihood of exposure to psychosocial risk related to job insecurity. A similar finding was reported in a study of workers in the textile industry in Turkey, where concerns about career prospects and job loss were among the least prominent sources of stress [14]. These findings suggest that job insecurity was not a prominent source of stress among the participants in the present study. Table 3 presents the mean score and standard deviation for perceived job insecurity.

Table 3: Perceived job insecurity

Measure	Mean	Standard deviation
Perceived job insecurity	2.6	0.10

3.3. Subjectively Perceived Main Source of Stress

Thirty-three participants (53.2%) answered the open-ended question, “What represents the greatest source of stress for you at work?” Qualitative analysis identified six specific categories of work-related stressors. Irregular and/or low pay was the most frequently reported specific stressor (17.7% of the total sample), followed by inadequate interpersonal relationships (11.3%) and excessive job demands (9.7%). One participant each identified lack of job control, fear of making mistakes, and physical working conditions related to heat. In addition, four participants (6.5%) reported that nothing caused them stress, while two participants (3.2%) indicated that several factors contributed to their stress.

Irregular and/or low pay was the most frequently reported specific source of stress. Previous research in the garment industry has linked inadequate or insecure pay with higher levels of work-related stress and poorer mental health among workers [13, 15].

The distribution of responses is presented in Table 4. Percentages in Table 4 are calculated relative to the total sample (N = 62).

Table 4: Subjectively perceived main sources of stress

Source of stress	Number of participants	%
Irregular and/or low pay	11	17.7
Inadequate interpersonal relationships	7	11.3
Excessive job demands	6	9.7
Lack of job control	1	1.6
Fear of making mistakes	1	1.6
Physical working conditions (heat)	1	1.6
Multiple stressors	2	3.2
None	4	6.5

3.4. Experienced Consequences of Exposure to Work-Related Stress

The largest proportion of participants (71.0%) reported consequences of exposure to work-related stress classified as Category A, which includes reduced work performance and brief episodes of distress accompanied by stress reactions. Category B consequences were reported by 8.1% of participants and include prolonged periods of reduced work performance, frequent

physical, cognitive, and emotional symptoms of stress, and short-term sick leave. No participant who answered this item selected Category C, which includes stress-related health problems, chronic fatigue, prolonged sick leave, continuously reduced work performance, and work avoidance. Overall, the reported consequences of work-related stress were predominantly mild and short-term.

This may indicate a relatively favourable situation in the participating companies; however, the organisational, environmental, and individual factors potentially contributing to this pattern were not directly assessed in the present study.

The distribution of participants across the consequence categories is shown in Table 5.

Table 5: Experienced consequences of exposure to work-related stress

Category	Number of participants	%
Category A	44	71.0
Category B	5	8.1
Category C	0	0.0
No response	13	21.0
Total	62	100.0

4. CONCLUSION

The study showed that workers in the textile industry are exposed to psychosocial risks at work, with limited job control showing the highest risk level among the assessed psychosocial risk domains. This refers to workers' limited ability to make decisions about aspects of their work such as work pace, the timing of rest breaks, the way tasks are performed, and flexibility in working hours. In the open-ended responses, irregular and/or low wages, interpersonal relationships, and excessive job demands were most frequently identified as specific sources of stress, which is consistent with previous research in the textile and garment industries.

Most participants reported mild and short-term consequences of exposure to work-related stress, while no participant who answered this item reported more severe consequences such as stress-related health problems, chronic fatigue, prolonged sick leave, continuously reduced work performance, or work avoidance. These findings suggest that severe stress-related health consequences were not prominent among the participants at the time of the study; however, there remains scope for improving work organisation and strengthening systematic prevention of psychosocial risks.

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Professional paper

THE ROME II REGULATION – ENVIRONMENTAL DAMAGE

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Abstract: *In order to ensure the maintenance and development of the area of freedom, security and justice within the EU, it is necessary to adopt measures in the area of judicial cooperation in civil matters with cross-border effects related to non-contractual obligations, including environmental damage. One of the measures is contained in the Rome II Regulation as a source of secondary law with binding application. With its solutions, the Rome II Regulation provides an answer to the question of what is damage to the environment and which law is determined as applicable. This paper shows the development path in the adoption of EU regulations in the field of tort law, answers the question of what environmental damage is and analyzes the provisions that regulate the applicable law.*

Keywords: *Regulation Rome II, environmental damage, applicable law*

1. INTRODUCTION

In the six-decade-long European integration process, today's EU has built and is still building its legal system based on the harmonization and unification of public and private law regulations [1]. In Europe, which is characterized by open borders and a multitude of cross-border legal relations, no lawyer can afford to miss this development [2]. Starting from the European integration process of the 1950 and the conclusion of treaties establishing three communities, the European Coal and Steel Community [3], the European Economic Community [4], and the European Atomic Energy Community [5], the subject of private international law was first regulated by Article 220 of the Treaty of Rome of 25 March 1957 [6], namely the area of recognition and enforcement of foreign decisions. After a period of "initial lull" [7], on the basis of Article 220 of the Treaty of Rome, eleven years later the development of European private international law continued with the adoption of the Brussels Convention on Jurisdiction and the Enforcement of Judgments in Civil and Commercial Matters of 27 September 1968 [8], and the Rome Convention on the Law Applicable to Contractual Obligations of 19 June 1980 [9].

These international treaties would later become sources of European secondary law, namely the Brussels Convention into European Council Regulation No. 44/2001 of 22 December 2000 on jurisdiction and the recognition and enforcement of judgments in civil and commercial matters [10]., and the Rome Convention into Regulation No. 593/2008 of the European Parliament and of the Council of 17 June 2008 on the law applicable to contractual obligations [11]. With the entry into force of the Maastricht Treaty on 1 November 1993 [12], a minor step forward in improving the position of private international law was represented by the provision contained in Article K. 1, Chapter VI entitled "Cooperation in the field of justice and home affairs." This provision defined judicial cooperation in civil matters as cooperation of common interest. Furthermore, with the entry into force of the Amsterdam Treaty on 1 May 1999 [13], the position of European private international law changed significantly [14].

The Treaty of Amsterdam, pursuant to Article 61 of the EC Treaty, empowered the Council to adopt various measures, including measures to achieve judicial cooperation in civil matters with a foreign element, in order to gradually establish a single area of freedom, security and justice, which is one of the objectives of the EC, to the extent necessary to ensure the functioning of the internal market [15]. Further integration was achieved with the entry into force of the Treaty of Nice on 1 February 2003 [16]. Until the entry into force of the EC Treaty in the Nice version, measures to achieve judicial cooperation in civil matters were adopted by the Council, and thereafter they are adopted jointly by the Council and the European Parliament in accordance with the codecision procedure provided for in Article 251 of the EC Treaty, except in the area of family law, when the measures are adopted by the Council alone [17].

The 2004 Treaty establishing a Constitution for Europe [18] provided that the EU would develop judicial cooperation in civil matters with an international dimension, based on the principle of mutual recognition of judicial and extrajudicial decisions. After the failure of the Treaty establishing a Constitution for Europe, the Treaty of Lisbon was drafted [19]. Finally, the Treaty of Lisbon specifically changes the previous general legal framework that regulated, among other issues, European private international law as a component of judicial cooperation in civil matters. [20] The Treaty of Lisbon represents a new stage in the process of creating an ever closer union among the peoples of Europe, in which decisions are taken as openly as possible and at a level as close as possible to the citizens (Article 1(2)). The EU is based on the Treaty of Lisbon and the Treaty on the Functioning of the EU, both of which have the same legal value (Article 1(3) (2-3)). The Union replaces and succeeds the EC (Article 1(3)). In addition to Article 67, the legal framework for European private international law is also contained in Chapter 3 of the Treaty of Lisbon, entitled "Judicial cooperation in civil matters", and is regulated by Article 81.

On the basis of the aforementioned treaties, more precisely within the framework of the institutions created by them, over the past five decades, literally thousands of legal acts, of a general and implementing nature, have been passed, which constituted a body of rules that, in the opinion of many, represents a special, supranational legal order. [21] This period from the establishment of the EU to the adoption and entry into force of the Rome II Regulation can be divided into two periods. In the first period, this issue was resolved through the conclusion of international agreements, and in the second period within the framework of EU secondary law, through a regulation as a source of secondary law with binding application in all member states.

Liability for damage from the aspect of determining the applicable law is contained in secondary sources. EU law includes all legal norms contained in the acts adopted by the member states for the purpose of establishing the EC and the EU, in the annexes and protocols of these acts, as well as in the acts that amended them (primary EU law), as well as all legal norms contained in the legal

acts adopted on the basis of these acts (secondary EU law) [22]. In order to exercise the powers of the Union, the institutions adopt regulations, directives, decisions, recommendations and opinions (Article 288 (1) of the Treaty of Lisbon). Article 288 (2) defines a regulation as follows: “A regulation shall have general application, be binding in its entirety and directly applicable in all Member States.” The Court of Justice of the EU was forced in its Costa/E.N.E.L. decision to draw the conclusion on the superior effect of EU law by inductive method, from EU regulations to the whole of EU law [23]. In Case C-6/64, on a request for a preliminary ruling under Article 177 of the EEC Treaty, submitted by the Giudice Conciliatore di Milano with a view to obtaining the interpretation of Articles 102, 93, 53 and 37 of the said Treaty in the case before that court: Flaminio Costa v. E.N.E.L. − Ente nazionale energia elettrica impresa già della Edisonvolta, the Court of Justice of the EU, in its judgment of 15 July 1964, took the position that: "National law cannot take precedence over the law arising from the Treaty, as a special source of law, due to its special and original nature." [24].

2. THE ROME II REGULATION

The adoption of the Rome II Regulation, after a significant forty years of searching for a comprehensive legal solution, unifies and federalizes the conflict-of-law rules of international tort law in the EU. Due to the intertwining of economic relations in the internal market, in which "third parties" very often participate, and because all disputes in the EU have a potential intra-EU character, the provisions of the Rome II Regulation apply universally [25]. Based on the principle of predictability and certainty in determining the applicable law for non-contractual liability for damage, the Rome II Regulation seeks to strengthen legal certainty as a guarantee for the realization of the principle of mutual recognition of foreign court decisions in civil and commercial matters [26].

The field of application of the Rome II Regulation is clearly indicated in its introductory part, and the provision contained in Article 1. Namely, it follows from the Introductory part: The Community has set itself the objective of maintaining and developing an area of freedom, security and justice. For the progressive establishment of such an area, the Community is to adopt measures relating to judicial cooperation in civil matters with a cross-border impact to the extent necessary for the proper functioning of the internal market (Preamble 1 Rome II). According to Article 65(b) of the Treaty, these measures are to include those promoting the compatibility of the rules applicable in the Member States concerning the conflict of laws and of jurisdiction (Preamble 2 Rome II). This Regulation shall apply from 11 January 2009, except for Article 29, which shall apply from 11 July 2008 (Article 32 Rome II). The Rome II regulation is binding in all member states. This Regulation shall apply, in situations involving a conflict of laws, to non-contractual obligations in civil and commercial matters. It shall not apply, in particular, to revenue, customs or administrative matters or to the liability of the State for acts and omissions in the exercise of State authority (acta iure imperii) (Article 1 Rome II).

3. NON-CONTRACTUAL OBLIGATIONS

The concept of a non-contractual obligation varies from one Member State to another. Therefore for the purposes of this Regulation non-contractual obligation should be understood as an autonomous concept. The conflict-of-law rules set out in this Regulation should also cover non-contractual obligations arising out of strict liability (Preamble 11 Rome II). For the purposes of this Regulation, damage shall cover any consequence arising out of tort/delict, unjust enrichment, negotiorum gestio

or culpa in contrahendo (Article 2 (1) Rome II). This Regulation shall apply also to non-contractual obligations that are likely to arise (Article 2 (2) Rome II). Any reference in this Regulation to: a) an event giving rise to damage shall include events giving rise to damage that are likely to occur; and b) damage shall include damage that is likely to occur (Article 2 (3) Rome II).

4. ENVIRONMENTAL DAMAGE

According to the provisions of the Rome II Regulation, Environmental damage should be understood as meaning adverse change in a natural resource, such as water, land or air, impairment of a function performed by that resource for the benefit of another natural resource or the public, or impairment of the variability among living organisms (Preamble 24 Rome II). Regarding environmental damage, Article 174 of the Treaty, which provides that there should be a high level of protection based on the precautionary principle and the principle that preventive action should be taken, the principle of priority for corrective action at source and the principle that the polluter pays, fully justifies the use of the principle of discriminating in favour of the person sustaining the damage. The question of when the person seeking compensation can make the choice of the law applicable should be determined in accordance with the law of the Member State in which the court is seised (Preamble 25 Rome II).

5. THE LAW APPLICABLE

The law applicable to a non-contractual obligation arising out of environmental damage or damage sustained by persons or property as a result of such damage shall be the law determined pursuant to Article 4(1), unless the person seeking compensation for damage chooses to base his or her claim on the law of the country in which the event giving rise to the damage occurred (Article 7 Rome II). Unless otherwise provided for in this Regulation, the law applicable to a non-contractual obligation arising out of a tort/delict shall be the law of the country in which the damage occurs irrespective of the country in which the event giving rise to the damage occurred and irrespective of the country or countries in which the indirect consequences of that event occur (Article 4 (1) Rome II). However, where the person claimed to be liable and the person sustaining damage both have their habitual residence in the same country at the time when the damage occurs, the law of that country shall apply (Article 4 (2) Rome II). Where it is clear from all the circumstances of the case that the tort/delict is manifestly more closely connected with a country other than that indicated in paragraphs 1 or 2, the law of that other country shall apply. A manifestly closer connection with another country might be based in particular on a pre-existing relationship between the parties, such as a contract, that is closely connected with the tort/delict in question (Article 4 (3) Rome II). From this provision of Article 4 it clearly follows that the aforementioned links on which the applicable law is based. The Rome II Regulation starts from the place of damage or the place of harmful consequences as the first, then the common habitual residence of both the injured party and the tortfeasor, the law of the closest connection and autonomy of will. Analyzing this special conflict rule, it is clear that it contains two alternative links designed in favor of the injured party, who is allowed a unilateral choice between them. In contrast, the injured party has no influence on whether the applicable law will be determined based on the *locus damni* or *locus actus* link [27]. The fact that the strictest possible laws will probably be applied is considered by some authors to be detrimental to the nature of conflict of laws rules, as this could create new obstacles to the realization of basic economic freedoms [28].

These rules apply if the parties do not choose the applicable law. The parties may agree to submit non-contractual obligations to the law of their choice: a) by an agreement entered into after the event giving rise to the damage occurred; or b) where all the parties are pursuing a commercial activity, also by an agreement freely negotiated before the event giving rise to the damage occurred. The choice shall be expressed or demonstrated with reasonable certainty by thecircumstances of the case and shall not prejudice the rights of third parties (Article 14 (1) Rome II). Where all the elements relevant to the situation at the time when the event giving rise to the damage occurs are located in a country other than the country whose law has been chosen, the choice of the parties shall not prejudice the application of provisions of the law of that other country which cannot be derogated from by agreement (Article 14 (2) Rome II). Where all the elements relevant to the situation at the time when the event giving rise to the damage occurs are located in one or more of the Member States, the parties' choice of the law applicable other than that of a Member State shall not prejudice the application of provisions of Community law, where appropriate as implemented in the Member State of the forum, which cannot be derogated from by agreement (Article 14 (3) Rome II).

6. CONCLUSION

In order to ensure the maintenance and development of the area of freedom, security and justice, in order to achieve one of its fundamental principles, the principle of legal certainty, the EU adopted the Rome II Regulation with the aim of strengthening confidence in the stability of legal relations. It is a regulation that has binding application in the Member States. This Regulation, in cases involving a conflict of laws, applies to non-contractual obligations in civil and commercial matters. The Regulation clearly states which non-contractual obligations it does not apply to. Environmental damage is regulated by the Rome II Regulation in Chapter II, entitled Torts/Delicts.

The solutions of the Rome II Regulation are focused on determining the applicable law. The Rome II Regulation lists in its provisions the links on which the applicable law is determined, and its basic assumption is the freedom of the parties to choose the applicable law. The Rome II Regulation starts from the principle of party autonomy, on the basis of which the parties can choose the applicable law. The choice of applicable law is made by agreement. The applicable law may be chosen for the event giving rise to the damage, but also by an agreement freely concluded by the parties before the event giving rise to the damage.

The adoption of the Rome II Regulation clearly emphasized the importance of the conflict-of-law solution. It is precisely on the basis of the free choice of applicable law that the parties are given flexibility and predictability on the one hand, and on the other hand, they are enabled to choose the law that best suits the protection of their interests. In this way, the Rome II Regulation provides the parties with a greater degree of predictability and certainty.

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Original scientific paper

THE ANALYSIS OF THE INDICATORS OF ENVIRONMENTAL IMPACT IN TOURISM IN ENVIRONMENTAL IMPACT STUDIES

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Abstract: *This paper examines the integration of environmental protection policy into tourism planning through the adoption of environmental indicators from the European Tourism Indicator System (ETIS 2013 and 2016). The study analyses eight Environmental Impact Assessment (EIA) studies and seven environmental protection elaborations related to tourism developments in Croatia. By comparing ETIS indicators with environmental impact assessments, the research identifies significant gaps in the application of measurable sustainability indicators. The findings show that ETIS indicators are only partially incorporated and are applied in a general and imprecise manner, limiting the monitoring of tourism-related environmental impacts. The paper highlights the need for stronger integration of environmental protection policy and ETIS indicators into tourism and spatial planning to support sustainable tourism development.*

Keywords: *sustainable tourism development, spatial interventions, ETIS, tourism infrastructure planning, environmental policy integration*

1. INTRODUCTION

Achieving sustainable tourism development requires a stronger integration of environmental policy into tourism planning and decision-making processes. Effective tourism planning depends on a comprehensive and integrated approach that recognizes the interdependence of economic development, environmental protection, infrastructure, and tourism services. Despite extensive research on sustainable tourism, important challenges remain regarding the effective integration of environmental considerations into tourism development and spatial planning processes [1,2,5,11,12].

Recent studies indicate that sustainable destination management increasingly depends on climate resilience, greenhouse gas emission reduction, stakeholder participation, governance quality, digitalisation, and the application of measurable sustainability indicators[3,7,10,16]. Contemporary tourism policies are increasingly focused on climate adaptation, resource efficiency, biodiversity conservation, carbon footprint reduction, and improving the quality of life of local communities.

At the same time, sustainability indicators have become essential tools for evidence-based decision-making, monitoring environmental impacts, and evaluating the long-term sustainability of tourism destinations. In this context, environmental policy integration refers to the incorporation of environmental objectives and considerations into decision-making processes across all relevant sectors and levels of governance [8]. Such an approach is particularly important in tourism because tourism development can generate significant pressures on natural resources, landscapes, biodiversity, water resources, and local communities.

To prevent negative consequences such as environmental degradation, overcrowding of tourist areas, landscape deterioration, excessive resource consumption, and increasing climate-related risks, tourism planning must include a clear development vision, appropriate management mechanisms, and comprehensive environmental impact assessment procedures [21]. Recent international initiatives additionally emphasize the importance of climate action in tourism, highlighting the need to reduce greenhouse gas emissions and strengthen the resilience of tourism destinations to climate change impacts.

This paper examines the contribution of the Environmental Impact Assessment Regulation [23]. and the European Tourism Indicator System (ETIS) developed in 2013 and 2016[4,6]. Although ETIS remains one of the most widely recognized frameworks for monitoring tourism sustainability, contemporary research increasingly expands its application through indicators related to climate resilience, carbon emissions, governance quality, digital transformation, and community well-being. The paper therefore analyses the extent to which ETIS environmental indicators are reflected in Environmental Impact Assessments and environmental protection studies related to tourism development projects. The findings contribute to a better understanding of how environmental policy can be more effectively integrated into tourism planning and spatial development processes in order to support sustainable tourism development.

2. LITERATURE REVIEW

Tourism is closely linked to space because it depends on the natural, cultural, and infrastructural resources of a destination. Therefore, tourism planning should be based on an integrated and sustainable approach that recognizes the interdependence of tourism development, environmental protection, and spatial planning. Sustainable tourism development implies the preservation of natural and cultural resources while ensuring their availability for future generations. In practice, however, tourism development is often driven by the expansion of accommodation capacities and the more intensive use of space, with insufficient consideration given to local specificities, environmental sensitivity, and carrying capacity. Such approaches frequently result in discrepancies between development objectives and the actual spatial, social, and environmental impacts of tourism development.

The assessment of sustainable tourism development largely depends on the application of appropriate indicators. Tanguay et al. (2013) [19] emphasize that continuous monitoring through sustainability indicators is essential for effective tourism management. However, the lack of available data, limitations of statistical systems, and difficulties in collecting reliable information continue to represent significant barriers to their implementation [8,22]. Due to the multidimensional nature of sustainability, there is no universally accepted set of indicators. Nevertheless, contemporary research confirms that sustainability indicator systems remain among the most important instruments

for destination management, environmental monitoring, and the implementation of sustainable development policies[3,10,16].

The development of sustainability indicators is generally based on scientific, political, and participatory approaches. The scientific approach focuses on systematic data collection, the political approach seeks to develop indicators that support decision-making processes, while the participatory approach emphasizes stakeholder involvement and consensus-building in defining sustainability objectives [17]. Recent studies further highlight the importance of community engagement, destination governance, climate resilience, and evidence-based decision-making as key elements of sustainable tourism management[18].

Numerous authors identify carrying capacity assessment as one of the fundamental elements of sustainable tourism planning. Nevertheless, tourism development is often influenced by short-term economic interests and political pressures aimed at increasing tourist arrivals and revenues. Such development practices may lead to environmental degradation, loss of destination identity, reduced quality of life for local residents, and weakened social cohesion within local communities [20,21,29]. More recent studies confirm that exceeding a destination's carrying capacity is one of the principal causes of overtourism, manifested through overcrowding, increased pressure on infrastructure and natural resources, deterioration of visitor experiences, and declining quality of life for local residents [32,34]. Overtourism occurs when tourism growth surpasses the ecological, physical, social, and psychological limits of a destination, generating negative impacts for both visitors and host communities[31,35].Consequently, contemporary destination management approaches emphasize the continuous monitoring of physical, environmental, and social carrying capacities, as well as the incorporation of destination resilience, climate risk, and community well-being indicators into tourism planning and management processes [32,30]. In this context, carrying capacity is no longer viewed solely as a limitation on visitor numbers but rather as a dynamic management instrument aimed at balancing the economic benefits of tourism with environmental conservation and residents' quality of life[33,36].

Previous studies have identified several key areas for monitoring tourism sustainability, including water and energy consumption, waste management, biodiversity conservation, transport impacts, climate change adaptation, cultural heritage preservation, community participation, tourist satisfaction, and the economic benefits generated by tourism [19]. More recent research additionally emphasizes climate resilience, greenhouse gas emissions, destination governance, digitalisation, community well-being, and destination competitiveness as essential dimensions of sustainable tourism assessment [3,7,10]. In Croatia, Environmental Impact Assessment (EIA) represents one of the most important instruments for integrating environmental policy into development planning processes. The Regulation on Environmental Impact Assessment [23] prescribes the assessment of potential impacts on population, human health, biodiversity, water, soil, air, climate, landscape, cultural heritage, and other environmental components. Its purpose is to ensure that potential adverse environmental impacts are identified, assessed, and mitigated before decisions regarding project implementation are made.

As a complement to the Environmental Impact Assessment procedure, the European Tourism Indicator System (ETIS) provides a more detailed set of indicators for monitoring tourism sustainability at the destination level. ETIS includes indicators related to transport, greenhouse gas emissions, climate change adaptation, water and energy consumption, waste management, biodiversity conservation, wastewater treatment, as well as noise and light pollution [4,6]. Although ETIS is not a mandatory instrument, numerous studies confirm its value in monitoring destination sustainability and supporting evidence-based decision-making through measurable indicators. In

particular, its role in assessing tourism-related environmental pressures, monitoring climate impacts, and evaluating the effectiveness of sustainable development policies at the destination level has been increasingly recognized.

Although numerous sustainability indicators can be established at the destination level, their practical implementation still depends on the availability of high-quality local and regional data. Therefore, the selection, adaptation, and application of appropriate indicators remain among the key challenges in measuring and managing sustainable tourism development. For this reason, the analysis of the application of ETIS indicators within Environmental Impact Assessments and environmental protection studies represents an important contribution to understanding the possibilities for more effective integration of sustainable development principles into tourism and spatial planning processes.

3. RESEARCH FRAMEWORK AND METHODOLOGY

This study applies a qualitative comparative research approach based on document analysis and content analysis of Environmental Impact Assessment (EIA) studies and environmental protection studies related to tourism development projects in Croatia. Content analysis is a widely used method for the systematic examination of documents and enables the identification and comparison of predefined categories within textual data.

Table 1. Structure of the analysed sample

Project category	Number of documents
Marinas and nautical tourism ports	5
Tourist resorts and hotels	4
Beaches and coastal infrastructure	3
Golf tourism developments	3
Total	15

The analytical framework was based on the environmental indicators contained in the European Tourism Indicator System[4,6]. ETIS was selected because it represents one of the most widely recognised European frameworks for monitoring tourism sustainability and provides measurable indicators for assessing environmental impacts at destination level. ETIS indicators cover biodiversity protection, landscape conservation, water and energy consumption, wastewater treatment, waste management, transport impacts, greenhouse gas emissions, climate change adaptation, noise and light pollution, and other environmental dimensions of tourism development. For the purposes of the analysis, a coding matrix was developed based on ETIS environmental indicators. Each analysed document was reviewed to determine whether ETIS environmental indicators were explicitly assessed through measurable criteria, indirectly addressed through descriptive environmental assessment, or not addressed. Based on the frequency and depth of indicator representation, the analysed indicator categories were subsequently classified as High, Medium, Low, Very Low, or Absent in order to facilitate comparative analysis across the two observation periods. The classification criteria were defined as follows: a "High" rating indicates that most indicators within a given category were explicitly represented, while "Medium", "Low", and "Very Low" indicate progressively lower levels of representation. "Absent" indicates that no evidence of the indicator category was identified in the

analysed documents. The classification was based on qualitative expert assessment rather than on a numerical scoring system. The frequency and level of representation of individual indicators were then compared across the analysed documents.

The results were subsequently grouped into two observation periods (2013–2018 and 2022–2026) and evaluated through comparative analysis. This approach enabled the identification of trends in the integration of sustainability indicators into Environmental Impact Assessment practice and the assessment of the extent to which ETIS indicators have become incorporated into environmental assessment procedures over time. Similar comparative approaches are commonly used in studies evaluating the implementation of tourism sustainability indicator systems and their role in policy-making and destination management. This study has several limitations that should be considered when interpreting the results. First, the analysis was based on a relatively small sample of environmental assessment documents and focused exclusively on tourism development projects in Croatia, which may limit the generalisability of the findings to other geographical and institutional contexts. Second, the assessment of ETIS indicator representation was based on qualitative content analysis and coding procedures, which involve a degree of interpretative judgement and may introduce a certain level of subjectivity despite the use of predefined evaluation criteria.

4. RESEARCH RESULTS AND DISCUSSION

4.1. Representation of ETIS Indicators in Environmental Impact Assessments and Environmental Protection Studies during the Period 2013–2018

The analysis of eight Environmental Impact Assessment (EIA) [14,15,23] studies and seven environmental protection studies prepared between 2013 and 2018 indicates a limited representation of the European Tourism Indicator System (ETIS) indicators in environmental assessment practice. The analysed documents primarily focused on assessing impacts on biodiversity, landscape, marine ecosystems, water resources, and protected natural areas, in accordance with the legal requirements of the Environmental Impact Assessment procedure.

Most ETIS indicators related to sustainable tourism management were either insufficiently represented or addressed only indirectly. Indicators concerning tourism mobility, greenhouse gas emissions, climate change adaptation, resource efficiency, residents' quality of life, and destination carrying capacity were generally not included as measurable assessment criteria. Environmental impacts were predominantly assessed qualitatively, while the application of quantitative sustainability indicators remained limited. The results suggest that environmental assessments during the observed period were primarily oriented towards regulatory compliance and the protection of individual environmental components, rather than towards the systematic monitoring of tourism sustainability through measurable indicators.

4.2. Representation of ETIS Indicators in Recent Environmental Impact Assessments (2022–2026)

The analysis of recent Environmental Impact Assessment studies related to tourism and nautical tourism development projects, including the nautical tourism ports of Ploče, Pakoštane, Kaštel Sućurac–Sustipan, and Cavtat, indicates a gradual shift towards a broader understanding of sustainability within environmental assessment procedures. These findings are consistent with the theoretical foundations of the European Tourism Indicator System (ETIS), which was developed as

an integrated framework for monitoring the environmental, economic, socio-cultural and governance dimensions of tourism sustainability [4,6]. While ETIS promotes a comprehensive indicator-based approach to destination management, the analysed Environmental Impact Assessment (EIA) studies and environmental protection studies reveal that environmental assessment practice in Croatia remains primarily focused on the evaluation of individual environmental components rather than on the systematic monitoring of sustainability outcomes.The predominance of indicators related to biodiversity protection, landscape preservation and water resource management observed in both analysed periods reflects the traditional role of Environmental Impact Assessment procedures, which are primarily designed to identify and mitigate adverse environmental impacts of development projects. Similar findings have been reported by Modica et al. (2018), who concluded that the implementation of ETIS across European destinations often remains partial, with environmental indicators being more frequently applied than social, governance and management indicators[38].The increased representation of climate change impacts, greenhouse gas emissions, resource efficiency and climate resilience indicators in studies prepared during the period 2022–2026 suggests a gradual alignment of environmental assessment practice with recent European sustainability policies and the Croatian Sustainable Tourism Development Strategy to 2030. This trend confirms observations by McLoughlin et al. (2020), who emphasised that sustainability indicator systems are increasingly being used to support evidence-based tourism planning and destination management [39].

Compared with the earlier period, recent studies devote greater attention to climate-related risks, environmental resilience, wastewater management, resource efficiency, the protection of marine ecosystems, and selected social impacts of tourism development. The growing influence of European sustainability policies and the Croatian Sustainable Tourism Development Strategy to 2030 is reflected in a stronger consideration of climate change adaptation measures, environmental monitoring, and sustainable natural resource management.

However, the results indicate that ETIS indicators have not yet been systematically integrated into Environmental Impact Assessment practice. Although certain ETIS-related themes are increasingly present in the analysed studies, indicators concerning tourism mobility, greenhouse gas emissions, destination carrying capacity, residents' quality of life, overtourism, and the tourism carbon footprint are still largely absent or only partially addressed.

4.3. Comparative Analysis of the Periods 2013–2018 and 2022–2026

A comparison of the two observed periods reveals a positive trend towards a broader understanding of sustainability within environmental assessment procedures. While studies prepared between 2013 and 2018 focused primarily on traditional environmental components, documents prepared between 2022 and 2026 increasingly incorporate issues related to climate change, resource efficiency, and selected aspects of sustainable development.

Despite this progress, the research results indicate that environmental assessment practice in Croatia continues to rely predominantly on sector-specific analyses of individual environmental components rather than on integrated sustainability assessment frameworks. ETIS indicators remain only partially represented and are still not used as a comprehensive system for monitoring tourism sustainability.

The findings confirm the initial assumption that ETIS indicators were weakly represented in Environmental Impact Assessment studies and environmental protection studies during the period 2013–2018. Although their presence has increased in more recent documents prepared following the adoption of the Croatian Sustainable Tourism Development Strategy to 2030 and recent European sustainability policies, their implementation remains partial and fragmented. This indicates the need for a stronger integration of measurable sustainability indicators into Environmental Impact Assessment procedures in order to improve evidence-based decision-making and support more effective planning for sustainable tourism development and destination management.

Table 2. Comparative representation of ETIS environmental indicators in environmental assessment documents

ETIS indicator category	2013–2018	2022–2026
Biodiversity protection	High	High
Landscape protection	High	High
Water quality and marine environment	High	High
Wastewater management	Medium	High
Water consumption	Low	Medium
Energy consumption	Low	Medium
Waste management	Medium	High

ETIS indicator category	2013–2018	2022–2026
Climate change impacts	Low	Medium–High
Greenhouse gas emissions	Very low	Medium
Transport impacts	Low	Medium
Noise pollution	Medium	Medium
Light pollution	Low	Medium
Bathing water quality	Medium	Medium
Quality of life of residents	Absent	Low–Medium
Carrying capacity of destination	Absent	Low
Overtourism indicators	Absent	Absent
Tourism carbon footprint	Absent	Low
Climate resilience indicators	Absent	Medium
Governance and stakeholder participation	Low	Medium
Digital monitoring of sustainability	Absent	Low

The data presented in Table 1 indicate significant differences in the representation of ETIS indicators between the analysed periods. In Environmental Impact Assessment studies and environmental protection studies prepared between 2013 and 2018, the greatest attention was devoted to traditional environmental components, such as biodiversity, landscape, the marine environment, and water resources. In contrast, indicators related to climate change, greenhouse gas emissions, residents' quality of life, destination carrying capacity, and sustainability governance were either weakly represented or entirely absent.

The analysis of more recent studies conducted between 2022 and 2026 reveals certain progress in the incorporation of sustainability-related elements. More frequent consideration is given to climate-related risks, resource efficiency, waste and wastewater management, and environmental resilience to development projects. A gradual shift towards the inclusion of social dimensions of sustainability and destination governance can also be observed.

However, the research findings confirm that ETIS indicators have not yet been systematically integrated into Environmental Impact Assessment procedures. Their application remains partial and fragmented, with indicators related to overtourism, tourism carbon footprint, residents' quality of life, and destination carrying capacity being particularly underrepresented. Therefore, it can be concluded that more recent documents demonstrate a gradual convergence towards the principles of ETIS, but not its full implementation within Environmental Impact Assessment practice. The findings are consistent with previous studies on the implementation of the European Tourism Indicator System (ETIS), which suggest that sustainability indicator frameworks are often only partially integrated into planning and assessment procedures [4,6,38]. Although recent environmental assessment documents demonstrate increased attention to climate resilience, resource efficiency and environmental monitoring, important dimensions of sustainable tourism management, including carrying capacity, residents' quality of life and overtourism, remain insufficiently represented. Similar challenges have been identified in other European destinations, where the practical implementation of sustainability indicators is frequently constrained by data availability, institutional coordination and regulatory limitations [39]. These findings indicate that Environmental Impact Assessment procedures in Croatia are gradually moving towards a broader sustainability perspective, but have not yet fully adopted the integrated approach promoted by ETIS [40].

5. CONCLUSION

The findings indicate that ETIS environmental indicators are only partially represented in the analysed Environmental Impact Assessment and environmental protection studies. Traditional environmental topics, such as biodiversity protection, landscape conservation, wastewater treatment, and waste management, are generally well covered, whereas indicators related to tourism carrying capacity, greenhouse gas emissions, climate change adaptation, resident satisfaction, and overtourism remain weakly represented or absent. Although some improvements can be observed in the more recent assessment documents, the overall integration of ETIS indicators into environmental assessment practice remains relatively limited. The results of the study suggest that the integration of measurable ETIS indicators into Environmental Impact Assessment procedures could significantly improve the monitoring of environmental impacts associated with tourism development and strengthen evidence-based decision-making in tourism and spatial planning processes. Unlike Environmental Impact Assessment procedures, which primarily focus on predicting the potential impacts of individual projects before their implementation, ETIS enables the continuous monitoring of environmental, economic, social, and governance-related impacts throughout the operational phase of tourism development. This allows for the evaluation of the actual effects of tourism projects on destinations and facilitates the timely identification of sustainability-related challenges, such as overtourism, increased resource consumption, or declining quality of life among local residents.

The value of ETIS lies in its integrated approach to sustainability, as it combines environmental protection, economic development, social well-being, and destination governance within a single indicator framework. Its application enables the systematic monitoring of tourism sustainability, the comparison of performance across destinations, and more effective tourism management based on measurable data. Therefore, ETIS should not be viewed as a substitute for Environmental Impact Assessment procedures but rather as a complementary tool capable of bridging the gap between project-level environmental assessment and the long-term management of sustainable tourism development.

A stronger integration of environmental policy, tourism policy, and spatial planning, supported by the application of ETIS indicators, could contribute to a more effective implementation of sustainable tourism development principles and enhance the long-term sustainability and resilience of tourism destinations. The findings of this study confirm that ETIS represents a valuable framework for linking Environmental Impact Assessment procedures with the principles of sustainable tourism management and can contribute to the establishment of a more integrated approach to tourism planning and destination governance. Future revisions of Environmental Impact Assessment methodologies could incorporate selected ETIS indicators as complementary monitoring tools, thereby strengthening the integration of sustainable tourism principles into environmental assessment and destination management practices.

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Professional paper

BY-PRODUCTS IN FOOD 3DP COMPOSITION: TOWARDS ZERO-WASTE FOOD SYSTEM

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Abstract: *This study explores the implementation of food by-products into food product compositions as a strategic approach to achieving zero-waste systems and enhancing nutritional value. Food by-product valorization encompasses a range of technological and biochemical methods for preparing waste materials into value-added products, thereby promoting the circular economy, while requiring further investigation into consumer acceptance and safety regulations.*

The integration of 3D food printing aligns with the highest levels of the food waste hierarchy by enabling the upcycling of nutrient-rich by-products back into the human food chain, thus preventing them from becoming lower-value waste. Using food industry by-products in 3D-printed desserts is one of the most exciting trends in sustainable gastronomy. This technology enables the transformation of 'waste' into high-value, visually appealing, and nutritionally rich meals.

Key words: *circular economy, food by-products, 3D food printing desserts, waste valorization, zero-waste food systems*

1. INTRODUCTION

The global food industry currently faces a profound dual challenge: meeting the escalating nutritional demands of a rapidly growing population while simultaneously mitigating the severe environmental degradation associated with food production. One of the most critical deficiencies within this sector is the generation of massive quantities of agri-food by-products, which are traditionally discarded as low-value waste. This linear “take-make-dispose” approach leads to substantial economic losses for manufacturers and drives environmental challenges, including greenhouse gas emissions and inefficient resource utilization. However, from the perspective of a circular economy, these industrial side-streams such as fruit and vegetable peels, seeds, pomace, and whey are not waste materials but rather highly undervalued, nutrient-rich resources. They are naturally abundant in vital bioactive compounds, including dietary fibers, antioxidants, polyphenols, and high quality proteins, making them ideal candidates for food revalorization [2]. Integrating these functional side-streams back into the human food supply chain represents a pivotal step toward achieving resilient, zero-waste food systems. Despite their nutritional density, incorporating fibrous or structurally complex by-products into conventional food formulations presents significant technological hurdles, particularly regarding texture, homogeneity, and consumer sensory acceptance. To overcome these limitations, three-dimensional food printing (3DFP) has recently emerged as a transformative digital manufacturing technology. Operating on the principle of controlled, layer-by-layer material deposition, 3DFP allows for the precise utilization of alternative matrices and upcycled ingredients. This technology provides an innovative pathway to repurpose rejected or underutilized raw materials such as jackfruit seeds or agricultural residues into highly customized, visually appealing and texturally optimized formulations tailored to specific consumer demographics [1]. Consequently, the synergy between circular economy principles and additive manufacturing opens up new frontiers in sustainable gastronomy. Utilizing food industry by-products as functional ingredients in 3D-printed desserts represents one of the most promising trends for increasing the baseline value of food waste. By combining precise ingredient dosing with advanced aesthetic customization, 3DFP effectively maximizes resource efficiency and minimizes surplus at both industrial and localized community levels. This paper explores the direct potential of various agri-food by-products as functional elements within 3D printing food inks [9]. Specifically, it analyzes the primary technological constraints, rheological behaviors, and environmental advantages of shifting from linear manufacturing to a zero-waste circular production model using advanced 3DP dessert compositions [11].

2. FOOD PROCESSING WASTE

Waste in the food industry is generated through multiple operations, including the reception, storage, preparation, processing and packaging of food. While this process creates waste, it also offers opportunities for financial gain and environmental sustainability through proper waste management. The processing phase produces waste rich in nutrients and energy, which can be repurposed as animal feed or as raw materials for new food production [7]. Pre-technological phases such as procurement, reception, and storage generate the majority of waste. Three primary factors contribute to these losses: inaccurate ordering, inadequate storage practices, and poor inventory control. Raw materials that are no longer usable due to aging or quality degradation are discarded before entering production. An analysis of the Belgian food industry revealed that a significant portion of losses is preventable when companies accurately plan production, purchase only necessary supplies, and manage inventory effectively. The processing and refining of raw

materials generate a large volume of waste; some results from non-utilizable natural components (peels, shells, bones), while some stems from recipe errors, incorrect dosing, equipment failures or malfunctioning machinery. Studies indicate that nearly 21% of companies identify their greatest losses during processing rather than packaging, citing poor internal transport, human error, product breakage, and issues with production line changeovers. For instance, when two products are filled on the same line, the transition between batches may result in a product that fails to meet the specifications of either, requiring disposal despite being hygienically safe [2]. Following production, additional waste occurs during storage, inventory control and distribution. Food waste arises from poor packaging management, damage during transport, breaks in the cold chain, or returns from retailers. Manufacturers report that returns and contractual obligations toward retailers, such as seasonal holiday assortments, lead to the accumulation of excess stock that cannot be sold in time, eventually becoming waste. According to European statistics, food production and processing contribute approximately 19% of total food waste in the EU, representing a significant share of the supply chain [1]. Facilities focus on the accurate measurement and monitoring of waste to reduce their footprint, alongside regular equipment maintenance, streamlining technological processes and employee education. Furthermore, factories have the capacity to transform various waste streams into valuable by-products, such as polyphenol and pectin extracts or materials for fermentation processes, thereby reducing financial and environmental losses. Overall, the processing of food raw materials is a critical intervention point where proper management can achieve the greatest resource savings and real progress toward a more sustainable food production system [1].

3. THE ZERO-WASTE CONCEPT AND APPROACH IN THE FOOD SECTOR

The “zero-waste” or waste-minimum concept represents a strategic mindset and lifestyle aimed at conserving all resources through responsible production, consumption, reuse, and recovery of products and packaging. The core objective is to ensure no discharge of material makes its way to land, water, or air where it could harm human health or the environment. While the term literally implies the complete elimination of waste, in practical application within the food sector, it refers to the maximum possible reduction of waste streams. This framework operates on five core principles, commonly known as the 5Rs: refuse, reduce, reuse, recycle and compost [1].

In everyday practice and institutional management, these principles dictate specific behaviors:

Refuse: Rejecting unnecessary items that inherently generate waste, such as single-use plastic shopping bags, excessive packaging, or promotional fliers.

Reduce: Minimizing the overall consumption and production of products with identical or highly similar purposes to avoid unnecessary surplus.

Reuse: Extending the lifecycle of a product through proper maintenance, or donating and selling underutilized items to others instead of discarding them.

Recycle: Processing materials so they can be remanufactured into new products, ensuring the minimum amount of debris ends up in landfills or oceans.

Compost: Facilitating the natural biological decomposition of organic matter to return essential nutrients directly back into the soil [8].

These five operational principles closely align with the comprehensive seven-step zero-waste hierarchy: rethink/redesign, reduce, reuse, recycle/compost, material recovery, residuals management, and unacceptable practices. Rethinking or redesigning serves as the primary preventative step, ensuring that products enter the market utilizing easily renewable, repairable, or fully recyclable materials. In the food sector specifically, a significant volume of edible material is discarded due to inadequate meal planning, purchasing surpluses, or a widespread lack of consumer understanding regarding expiration dates. Implementing a zero-waste approach encourages conscious inventory management at both industrial and household levels. Practical household interventions include creating strict grocery lists, establishing regular refrigerator inventory checks, and adhering to the “first-in, first-out” (FIFO) principle for older ingredients. Furthermore, culinary leftovers can be intentionally repurposed into new dietary formulations such as soups, stews, or spreads rather than being discarded. Within modern waste reduction frameworks, advanced manufacturing technologies like three-dimensional food printing (3DFP) are increasingly recognized as vital tools to operationalize these zero-waste principles by converting rejected, misshapen produce or processing scraps into functional, high-value meals [11].

4. 3D FOOD PRINTING FOR WASTE-FREE SYSTEMS

Wong et al. (2022) state that 3D food printing (3DFP) is an emerging technology that can be effectively utilized for processing food waste from various sources [9]. However, consumer acceptance of food waste as an edible ingredient still faces numerous barriers. 3DFP technology can facilitate the repurposing of certain types of waste by creating customized, personalized, and aesthetically pleasing products with familiar flavors and shapes, thereby increasing consumer acceptance. The same authors (2022) demonstrate the 3D printability of jackfruit seeds, which are often underutilized and discarded as waste. Many food upcycling projects primarily focus on industrial food waste, as it is centralized, relatively simple in composition, and well-characterized, offering greater economic potential for recycling and upcycling [9]. However, in developed countries, the majority of food waste is generated at the household level. Upcycling such waste is technically, logistically, and economically challenging due to wide geographical dispersion and complex composition. 3D food printing technology can be used to decentralize food waste upcycling to the level of local communities. 3D food printing operates on the principle of creating a digital food product layer-by-layer using ‘edible filaments.’ In recent years, 3D food printing has gained significant attention because the resulting products can be fully customized in terms of appearance, composition, and additives for any desired food item. To date, foods such as cheese, fruit, and chocolate have been 3D printed and utilized 3D printing to print vegetables like carrots, peas, and pak choi, with potential applications in diets for individuals with dysphagia (swallowing difficulties). The 3D printing technology is particularly suitable for processing food waste that is rarely consumed in households, such as jackfruit seeds. It is consumed fresh when ripe or processed into snacks and canned products. Jackfruit seeds account for approximately 10–15% of the fruit’s mass, range from 2 to 4 cm in length, and each fruit contains between 100 and 500 seeds. Due to their perishable nature, they are often discarded as waste, representing a neglected and underutilized source of nutrients. Although the full nutritional value of jackfruit seeds has not yet been exhaustively researched, they are known to be a rich source of starch, proteins, fiber, and magnesium essential for bone health and blood pressure regulation [9]. Wong et al. (2022) note that at least one study explores the application of 3D printing in upcycling food waste derived from jackfruit seeds. That research utilized two dough formulations based on jackfruit seed powder and finger millet, with additives such as butter, xanthan gum, and soy protein isolate, to 3D print cookies [9]. The study emphasized the importance of proper ingredient

selection and printing parameters to achieve high-quality 3D printed cookies, where 3D printing was used to ensure uniform layering and improved texture. 3D food printing shows highly positive results and potential for further advancement in producing food items that could enhance human health by incorporating essential nutrients into 3D-printed products [11]. By prioritizing upcycling and prevention, innovative technologies like 3DFP ensure that food "waste" is treated as a valuable ingredient, moving it to the top of the hierarchy [10].

5. CONCLUSIONS

Achieving zero-waste food systems requires a strategic shift towards valorizing agri-food by-products, utilizing technologies like 3D food printing to convert side-streams into high-value nutrients. This approach reduces environmental impact and improves resource efficiency by reincorporating waste into the food chain. By integrating these materials back into the food chain, the industry can significantly reduce its environmental footprint and economic losses. 3D food printing (3DFP) emerges as a transformative tool in this process. Furthermore, 3DFP supports the highest levels of the food waste hierarchy through precision dosing and on-demand production, effectively preventing surplus and minimizing waste at both industrial and household levels. In conclusion, achieving a sustainable, waste-free future requires a shift in mindset-from viewing by-products as "waste" to treating them as valuable "ingredients." While challenges regarding consumer acceptance and large-scale implementation remain, the synergy between circular economy principles and 3D printing technology provides a robust framework for a more resilient and responsible global food system.

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Original scientific paper

SOIL-REMOVAL EFFICIENCY IN ECO-FRIENDLY WASHING OF FUNCTIONALISED COTTON/ POLYESTER FABRICS

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Abstract: *This study investigates the soil-removal efficiency of untreated, cationised, and antimicrobial-treated cotton/polyester fabrics under modified, more sustainable washing conditions. A standardised washing procedure at 75 °C was modified by reducing the washing temperature to 50 °C, using a non-ionic surfactant, and replacing peracetic acid with the more environmentally favourable bleaching agent ε-phthalimido-peroxyhexanoic acid (PAP), while protease enzyme was selectively applied. Washing performance was evaluated based on the removal of four representative stains – red wine, egg yolk, shoe polish, and ketchup – after a single washing cycle. Soil-removal efficiency was determined from changes in fabric remission before and after washing. The results demonstrate that appropriately selected low-temperature washing systems based on a non-ionic surfactant detergent system, PAP, and enzyme treatment can provide effective soil removal from functionalised cotton/polyester fabrics while offering potential for more sustainable textile care.*

Keywords: *soil-removal efficiency, functionalised cotton/polyester fabrics, low-temperature washing, sustainable textile care*

1. INTRODUCTION

Over the past two decades, increasing environmental awareness and the principles of sustainable development and green chemistry have driven significant changes in detergent formulation and textile washing technology. The focus has increasingly shifted towards reducing energy and chemical consumption, particularly through lower washing temperatures and the use of more environmentally favourable washing agents, while maintaining effective soil removal [1-3]. Washing is a complex process determined by the combined effects of temperature, time, mechanical action, washing solution composition, and chemical auxiliaries [4,5]. The use of enzymes and environmentally favourable bleaching agents, such as ε-phthalimido-peroxyhexanoic acid (PAP), can enable effective washing under milder conditions [3,4]. Lower-temperature washing is particularly important, as it can reduce energy consumption while still providing effective washing performance [1-3]. At the same time, the increasing application of functional finishes to textile fabrics may alter fibre-surface properties and interactions with soils and washing components, thereby affecting washing performance. Cationisation introduces cationic sites and alters the surface charge

of the fibres [6], potentially modifying soil–fibre and detergent interactions and, consequently, soil removal during washing. Antimicrobial treatments may also change the surface characteristics of the textile substrate and thus influence interactions between the fabric and deposited soil. The effectiveness of a washing process is determined by its ability to remove deposited soil from textile materials during the washing cycle, making soil removal efficiency a key criterion for evaluating washing performance. Soil removal efficiency can be affected by several factors, including the type and characteristics of the soil, the properties of the textile substrate, and the composition of the washing solution [7].

The aim of this study was to investigate the soil-removal efficiency of untreated, cationised, and antimicrobial-treated cotton/polyester fabrics under modified, lower-temperature washing conditions. The influence of water, ε-phthalimido-peroxyhexanoic acid (PAP), protease enzyme, and their combination on the removal of four different soils – red wine, egg yolk, shoe polish, and ketchup – was evaluated, with particular emphasis on the effects of fabric functionalisation and thermocondensation treatment.

2. MATERIAL AND METHODS

In this study, a satin-weave fabric composed of a 50/50 cotton/polyester blend, with a mass per unit area of 163.6 g/m², was used. The untreated fabric (U) was first cationised (C) [6], and then functionalised antimicrobially [8]. Antimicrobial treatment was thermocondensed at 150 °C after a continuous process (C-AC) on a Benz stenter, or after a discontinuous process (C-AD) on a heat press. The designations of the untreated and treated fabric samples are presented in Table 1.

Table 1: Designations of the untreated and treated fabric samples

Sample	Description
U	Untreated, pristine satin-weave fabric
C	Cationised fabric
C-AC	Cationised and antimicrobial-finished fabric, continuously pad-dry-cured
C-AD	Cationised and antimicrobial-finished fabric, discontinuously heat-cured

For the assessment of soil-removal efficiency of the functionalised fabrics, four representative stains were selected: red wine, egg yolk, shoe polish, and ketchup. The selected stains represent different soil characteristics, including coloured, proteinaceous, and pigment-rich soils, thereby providing a range of washing challenges. The treated fabric samples (70 × 10 cm) were manually soiled using the selected stains, with a nominal stain diameter of 3 cm. The red wine stains were larger because of capillary spreading through the fabric structure. The horizontally positioned specimens were left to air-dry for 24 h and were then subjected to the defined washing procedures.

The washing programme in EN ISO 15797:2018 for the relevant polyester/cotton fabric specifies standardised test procedures at 75 °C with peracetic acid bleaching. This standard provides several washing procedures, allowing selection according to the characteristics of the textile material and its intended use. The washing programme was modified by reducing the washing temperature to 50 °C and replacing peracetic acid with ε-phthalimido-peroxyhexanoic acid (PAP). Protease enzyme was selectively applied for the treatment of proteinaceous soil. In addition, a combined PAP and enzyme treatment was also investigated. The washing process was carried out in a Wascator FOM71 CLS

(Electrolux) with non-ionic detergent at a concentration of 4 g/L, a bath ratio of 1:4, 2 g/L bleach additive, and 0.1 g/L enzyme. The washing solution combinations are schematically presented in Figure 1.

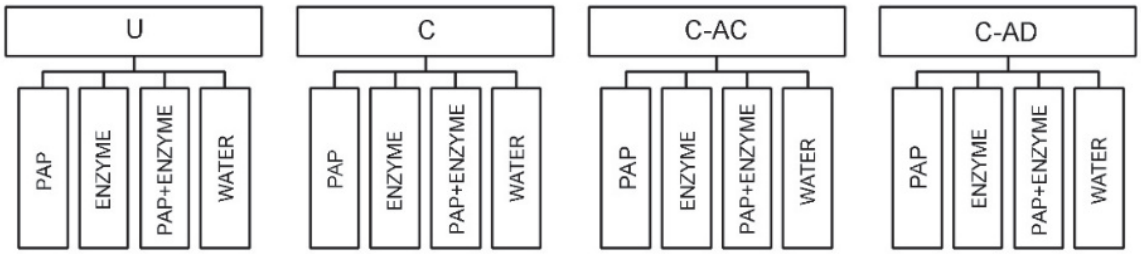


Figure 1: Schematic representation of the washing process with associated selected fabrics and washing bath combinations

Soil-removal efficiency was evaluated based on stain removal. Washing performance (detergency) was assessed from the change in reflectance between the unwashed and washed stain using a Spectraflash SF 300 remission spectrophotometer (Datacolor). The spectral characteristics were measured using a 20 mm aperture, standard D65 illuminant, and a measurement range of 360–700 nm. The spectral values of each washed stain were measured at four randomly selected positions per sample. The washing performance was expressed as the difference between the reflectance of stain after washing (R_w) and reflectance of the stain before washing (R_0), both at a wavelength of 460 nm, according to the following equation:

$$\Delta R_{(460)} = R_{w(460)} - R_{0(460)} \quad (1)$$

Overall washing efficiency at 50 °C was evaluated by summing the $\Delta R_{(460)}$ values obtained for the four tested stain types (ΣR_{460}).

3. RESULTS

In this research, four different stains – red wine, egg yolk, shoe polish, and ketchup – were selected as representative stains with distinct characteristics to provide a broader assessment of soil-removal efficiency and to investigate how the applied fabric functionalisation treatments and the composition of the washing solution affect their removal. Because the present study assesses soil removal after a single washing cycle, the results are reported as the change in remission at 460 nm. The discussion below therefore focuses on the relative contributions of PAP, enzyme, and their combination to soil removal for each fabric treatment. The washing-efficiency results are presented for the experimentally applied stains. The effects of PAP, proteolytic treatment, and their combination were compared with washing in water to estimate the contribution of the washing auxiliaries. Soil-removal efficiency was calculated from four instrumental measurements per stain and expressed $\Delta R_{(460)}$; overall washing efficiency across the four stains was expressed as ΣR_{460} and is presented in Tables 2–5 and Figure 2.

Table 2. Soil-removal results for **untreated** samples washed with detergent solutions containing **PAP, enzyme, combination of PAP and enzyme,** and **water**

	Fabric treatment	Washing liquor					
	U	PAP					
STAINS	R_{0460}	1	2	3	4	R_{w460}	ΔR_{460}
red wine	54.20	76.44	75.67	76.38	76.31	76.20	22.00
egg yolk	5.08	70.55	70.25	70.29	70.89	70.50	65.42
shoe polish	5.78	13.64	15.01	15.96	13.71	14.58	8.80
ketchup	4.14	75.11	75.71	74.75	75.70	75.32	71.18
	U	ENZYME					
red wine	54,20	73,44	73.04	73.56	73.33	73.34	19.14
egg yolk	5,08	75,59	75.12	74.28	75.78	75.19	70.11
shoe polish	5,78	16,61	15.79	15.69	14.70	15.70	9.92
ketchup	4,14	74,70	74.83	73.95	74.09	74.39	70.25
	U	PAP + ENZYME					
red wine	54.20	76.30	75.11	75.68	75,62	75,68	21,48
egg yolk	5.08	71.36	72.57	72.67	71,05	71,91	66,83
shoe polish	5.78	15.60	17.33	17.13	16,68	16,69	10,91
ketchup	4.14	74.08	74.36	75.88	75,88	75,05	70,91
	U	WATER					
red wine	54.20	70.77	70.70	70.34	70,56	70,59	16,39
egg yolk	5.08	35.48	36.87	37.21	55,91	41,37	36,29
shoe polish	5.78	9.24	9.50	10.24	8,79	9,44	3,66
ketchup	4.14	71.07	68.56	70.96	70,42	70,25	66,11

Water contributes to washing by dissolving water-soluble soil and through the thermal and mechanical actions that occur during the wash. In the untreated fabric (Table 2), the PAP + enzyme treatment produced the highest overall soil removal value, expressed as the sum of ΔR_{460} values across the four stains (170.13), closely followed by the enzyme alone (169.43). For the egg-yolk stain, enzyme treatment resulted in the highest ΔR_{460} value (70.11), indicating a marked contribution of proteolytic activity to the removal of this proteinaceous soil. Despite showing the lowest overall washing performance, the water treatment quantified the contribution of the washing process itself to soil removal and demonstrated that mechanical and thermal actions contributed to stain removal even in the absence of PAP or enzyme.

The cationised samples (Table 3) showed substantially lower overall soil-removal values than the untreated fabric. Cationisation introduces positively charged sites on the fibre surface, which may promote electrostatic interactions with negatively charged soil components and thereby influence soil–fibre interactions during washing. Among the four washing treatments, enzyme treatment produced the highest overall soil-removal value (112.96), followed by PAP + enzyme (107.54), PAP (106.19), and water (98.27). However, the response varied considerably among the individual stains. Notably, water treatment resulted in the highest ΔR_{460} for egg yolk (72.30), whereas enzyme treatment showed the highest values for red wine and shoe polish.

For the continuously thermocondensed antimicrobial-treated samples (C-AC, Table 4), the four washing treatments produced very similar overall soil-removal values, ranging from 128.09 to 132.14. Water treatment showed the highest overall value (132.14), followed by PAP (130.35), PAP + enzyme (129.75), and enzyme treatment (128.09). The maximum difference between the treatments was only 4.05 units, indicating that, under the present experimental conditions, the washing auxiliary had a relatively limited effect on the overall soil-removal performance of the continuously treated fabric.

Table 3: Soil-removal results for **cationised** samples washed with detergent solutions containing **PAP, enzyme, combination of PAP and enzyme,** and **water**

	Fabric treatment	Washing liquor					
	C	PAP					
STAINS	R_{0460}	1	2	3	4	R_{w460}	ΔR_{460}
red wine	54.24	50.32	50.45	50.56	49.91	50.31	-3.93
egg yolk	8.25	65.87	58.92	64.93	72.25	65.49	57.24
shoe polish	5.22	7.41	8.23	7.93	8.40	7.99	2.77
ketchup	8.31	59.43	57.84	57.34	59.03	58.41	50.10
	C	ENZYME					
red wine	54.24	46.74	46.74	45.80	47.29	46.64	-7.60
egg yolk	8.25	71.67	71.35	72.24	70.98	71.56	63.31
shoe polish	5.22	12.03	11.30	10.17	13.77	11.82	6.60
ketchup	8.31	59.39	59.69	58.69	58.08	58.96	50.65
	C	PAP + ENZYME					
red wine	54.24	49.04	49.01	49.46	49.91	49.36	-4.89
egg yolk	8.25	69.76	67.67	69.47	68.64	68.89	60.64
shoe polish	5.22	7.68	10.63	10.25	8.39	9.24	4.02
ketchup	8.31	56.57	55.80	56.07	55.89	56.08	47.77
	C	WATER					
red wine	54.24	37.01	36.31	36.14	36.94	36.60	-17.64
egg yolk	8.25	80.63	80.51	80.46	80.60	80.55	72.30
shoe polish	5.22	11.20	8.79	11.81	10.37	10.54	5.32
ketchup	8.31	51.77	46.35	45.45	42.82	46.60	38.29

Table 4: Soil-removal results for **antimicrobial continuously thermocondensation** samples washed with detergent solutions containing **PAP, enzyme, combination of PAP and enzyme,** and **water**

	Fabric treatment	Washing liquor					
	C-AC	PAP					
STAINS	R_{0460}	1	2	3	4	R_{w460}	ΔR_{460}
red wine	54.89	52.99	53.31	54.15	53.21	53.42	-1.47
egg yolk	4.74	71.57	69.23	72.32	69.35	70.62	65.88
shoe polish	5.28	12.23	12.79	12.64	13.01	12.67	7.39
ketchup	7.70	67.94	64.13	67.37	65.58	66.26	58.56
	C-AC	ENZYME					
red wine	54.89	50.41	50.56	50.74	51.23	50.74	-4.16
egg yolk	4.74	74.36	74.51	74.04	74.24	74.29	69.55
shoe polish	5.28	12.43	12.69	12.27	14.15	12.89	7.61
ketchup	7.70	60.76	63.72	63.50	63.19	62.79	55.09
	C-AC	PAP + ENZYME					
red wine	54.89	53.00	52.61	52,50	52.31	52.61	-2.29
egg yolk	4.74	75.25	74.05	74.97	74.36	74.66	69.92
shoe polish	5.28	12.57	11.87	10.39	14.47	12.33	7.05
ketchup	7.70	62.59	65.99	61.29	61.20	62.77	55.07
	C-AC	WATER					
red wine	54.89	55.73	55.16	55.94	55.74	55.64	0.75
egg yolk	4.74	75.14	71.85	74.45	71.69	73.28	68.54
shoe polish	5.28	10.20	9.03	9.90	9.97	9.78	4.50
ketchup	7.70	66.75	67.25	67.06	63.14	66.05	58.35

For the discontinuously thermocondensed antimicrobial-treated samples (C-AD, Table 5), larger differences in overall soil-removal performance were observed among the washing treatments. Soil-removal efficiency decreased in the order enzyme (139.14) > PAP + enzyme (126.69) > PAP (118.82) > water (118.64). The difference between the highest and lowest overall values was 20.50 units. The higher overall value for the enzyme treatment indicates that enzymatic treatment contributed substantially to soil removal in the discontinuously thermocondensed fabric under the current washing conditions.

Table 5: Soil-removal results for a**ntimicrobial discontinuously thermocondensation** samples washed with detergent solutions containing **PAP, enzyme, combination of PAP and enzyme,** and **water**

	Fabric treatment	**Washing liquor**					
	C-AD	**PAP**					
STAINS	**R_{0460}**	**1**	**2**	**3**	**4**	**R_{w460}**	**ΔR_{460}**
red wine	54.22	51.61	50.01	51.53	52.51	51.42	-2.81
egg yolk	4.83	65.18	62.38	66.82	65.73	65.03	60.20
shoe polish	6.89	10.53	11.09	10.87	9.92	10.60	3.71
ketchup	4.04	61.71	63.10	61.52	60.68	61.75	57.71
	C-AD	**ENZYME**					
red wine	54.22	57.68	57.51	58.21	57.15	57.64	3.42
egg yolk	4.83	74.29	74.06	74.51	74.54	74.35	69.52
shoe polish	6.89	14.92	14.91	13.84	16.30	14.99	8.10
ketchup	4.04	63.12	61.26	61.94	62.25	62.14	58.10
	C-AD	**PAP + ENZYME**					
red wine	54.22	54.42	53.50	54.47	54.61	54.25	0.03
egg yolk	4.83	73.39	73.94	73.56	72.93	73.46	68.63
shoe polish	6.89	11.25	11.49	12.10	12.17	11.75	4.,86
ketchup	4.04	54.46	62.75	53.02	58.62	57.21	53.17
	C-AD	**WATER**					
red wine	54.22	57.27	59.94	38.75	58.01	53.49	-0.73
egg yolk	4.83	59.39	64.99	71.20	41.31	59.22	54.39
shoe polish	6.89	8.99	11.57	8.90	9.25	9.68	2.79
ketchup	4.04	66.10	65.82	65.75	67.24	66.23	62.19

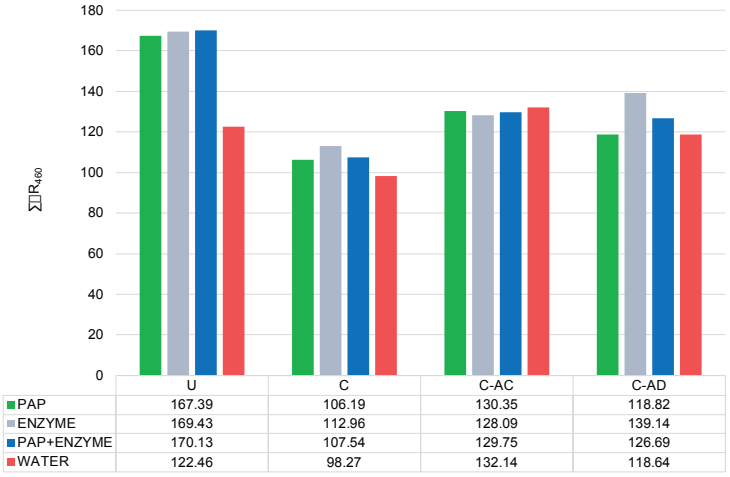


Figure 2: Total soil removal effect by washing solution used

Figure 2 shows that the cationised fabric achieved the lowest overall soil-removal values among the four fabric treatments. Water treatment was generally associated with the lowest overall soil-removal value, except for the continuously thermocondensed antimicrobial-treated fabric (C-AC), for which water produced the highest overall value. This result indicates that, for C-AC, the mechanical and thermal actions of the washing process contributed substantially to soil removal even in the absence of PAP or enzyme. The continuous antimicrobial treatment produced relatively similar overall results across the four washing solutions, whereas the discontinuous treatment showed greater sensitivity to the composition of the washing solution.

The continuous and discontinuous thermocondensation routes produced different soil-removal profiles. The continuous treatment showed relatively small differences among washing liquors, whereas the discontinuous treatment showed a pronounced advantage for the enzyme-containing liquor. A possible explanation is that the finishing route altered the surface properties and therefore the interaction between the deposited soil and the fibre surface; however, partial removal of the antimicrobial finish during washing was not directly measured in this study and should therefore be regarded only as a hypothesis.

4. CONCLUSION

The results show that soil-removal efficiency depends on both the type of fabric functionalisation and the composition of the washing liquor. Enzyme treatment was consistently effective in removing egg-yolk soil. For untreated fabric, the combination of PAP and enzyme treatment gave the highest overall soil-removal performance; however, this combination was not consistently superior for egg-yolk soil. Water alone also contributed measurably to the washing process through its thermal and mechanical effects. Cationisation generally reduced soil-removal efficiency, while the thermocondensation method affected the washing behaviour of antimicrobial-treated fabrics. Overall, the findings indicate that appropriately selected eco-friendly washing systems can achieve effective soil removal while potentially allowing lower washing temperatures and reducing reliance on conventional high-temperature bleaching systems.

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Original scientific paper

YOUNG PEOPLE'S ATTITUDES TOWARD CLIMATE CHANGE IN SERBIA: A CASE STUDY OF STUDENTS AT THE FACULTY OF OCCUPATIONAL SAFETY IN NIŠ

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Abstract: *This study examines young people's attitudes toward climate change in Serbia, with a case study of students at the Faculty of Occupational Safety in Niš. Data were collected through the "Youth and Climate Change" survey. The findings indicate a generally high level of awareness of climate change and its impacts on biodiversity, human health, and extreme weather events. Industrial activities, transport, and inadequate waste management were identified as the main causes. The internet, social media, and formal education were the main sources of information. Higher awareness and engagement were observed among female and older respondents. Despite high awareness and willingness to act, a gap remains between knowledge and individual behaviour. The findings highlight the need for stronger climate education and greater opportunities for young people to participate in environmental action.*

Keywords: *climate change; young people; students; attitudes; environmental awareness; environmental behaviour; climate education; Serbia.*

1. INTRODUCTION

Climate change has become one of the defining challenges of our time, and young people are increasingly at the centre of both its consequences and its possible solutions [1]. The impacts of climate change are no longer distant or abstract—they are already visible in everyday life across the world. For this reason, scientists and policymakers alike stress that immediate and coordinated action is necessary (e.g. [2]). In many ways, today's young generations are growing up in a world shaped by environmental uncertainty, while at the same time preparing to become the ones who will make key decisions about how society responds.

At the same time, young people are not only future decision-makers but also a group that directly experiences the consequences of previous environmental and political choices. In Serbia, there has been a noticeable rise in youth interest and engagement in environmental issues in recent years, reflected through various initiatives, associations, and forms of activism. Still, despite this growing visibility in public discourse, we still know relatively little about how young people in Serbia actually think about climate change and how they translate their awareness into behaviour.

This lack of evidence is what motivated the present study. Since research on Serbian youth in this field remains limited, we draw on findings from broader regional studies. For instance, Šimac et al. [19] show that between 2008 and 2018, support for environmental protection increased significantly in several Central European countries, including the Czech Republic, Hungary, Poland, Slovakia, and Slovenia. At the same time, a number of studies suggest that demographic factors alone do not strongly explain environmental attitudes, with education standing out as one of the few more consistent influences [4–7].

Research by Ančić et al. [3], based on ISSP data, further shows that people who are more aware of climate change and more concerned about environmental issues are also more willing to accept personal sacrifices in order to support environmental protection. This points to the importance of knowledge and awareness, but also reminds us that environmental attitudes are shaped by deeper value systems, social norms, and broader worldviews [8–10].

So far, most studies focusing on young people have relied on relatively small or non-representative samples [11–13], or have been conducted as part of student theses [14–15]. Even so, they consistently suggest that young people are generally aware of environmental problems and often express a willingness to contribute to environmental protection [16–18]. However, their engagement tends to lean toward more direct, practical, and easily accessible forms of action [12,15].

International findings also indicate that young people are at least as concerned about climate change as older generations, and in some cases even more so. Research from countries such as Australia, Germany, and the United States [19–21] shows a recurring pattern in which young women tend to report higher levels of concern than young men. Similar tendencies are observed in regional studies as well, where female students often show slightly stronger environmental awareness and more positive attitudes toward environmental protection [11,14]. In a broader European perspective, Henn, Sloam, and Nunes [22] also find that young women are more likely to engage in environmental activism than young men, while education appears to play an important role in shaping civic and environmental engagement. Altogether, these findings suggest that education systems may be one of the key spaces where environmental awareness and action can be strengthened.

In Serbia, however, climate change is not taught as a separate subject within the formal education system. Instead, environmental topics are integrated into existing subjects such as *The World Around Us*, *Nature and Society*, and *Biology* [12]. Compared to the amount of research on curriculum content, there is still relatively little understanding of how school actually shapes young people's environmental attitudes and behaviour. What we do know so far suggests that students themselves often feel they do not have enough opportunities to learn about environmental issues within education [16,17].

2. MATERIALS AND METHODS

The target population of the study comprised young people aged 15–29 years, while the empirical sample consisted of students within this age group enrolled at the Faculty of Occupational Safety in Niš, Serbia. Thus, the surveyed students represent a specific subgroup of the broader youth population defined for the purposes of the study. The final sample consisted of 150 fully completed questionnaires. Given that the sample was drawn from a single higher-education institution, the findings describe the attitudes, perceptions, and behavioural intentions of the surveyed student population and cannot be generalized to the entire population of young people in Serbia.

The majority of respondents were from urban areas (82%), as shown in Figure 1. The sampling approach can be described as an online voluntary response sample within a defined student population. All students of the Faculty were given access to the questionnaire, but participation depended on individual willingness to complete it. In this sense, the study does not claim full representativeness, but it provides useful insights into the attitudes of the surveyed group.

The survey was conducted using Google Forms, and data were collected between May and December 2024. The questionnaire was developed specifically for the purposes of this study, based on the research objectives and relevant literature on climate-change awareness, environmental attitudes, and pro-environmental behaviour. The questionnaire consisted of several groups of items addressing respondents' socio-demographic characteristics, awareness of climate-change causes and consequences, perceptions of responsibility for addressing climate-related problems, sources of information, willingness to learn about climate change, and intentions to engage in environmentally responsible behaviour. Both closed-ended and open-ended questions were included. Closed-ended questions were used to obtain quantitative indicators and were analysed using descriptive statistics, primarily frequencies and percentages. Open-ended questions were included to allow respondents to provide additional explanations and personal views; these responses were reviewed qualitatively and used to complement and contextualize the quantitative findings. The questionnaire was administered anonymously and participation was voluntary.

Anonymity was guaranteed to all respondents, which contributed to more honest and reliable answers. Data were analysed using IBM SPSS Statistics. Descriptive statistical procedures were applied to summarize the characteristics of the sample and respondents' answers. Frequencies and percentages were calculated for categorical variables, while means and standard deviations were used for continuous or scale-based variables, where applicable. Differences in responses between demographic groups were presented descriptively and were not subjected to statistical significance testing. Therefore, the observed differences between groups should be interpreted as descriptive patterns within the surveyed sample rather than as statistically significant differences that can be generalized to the wider population.

The aim of the quantitative research was to assess climate-change awareness among young people aged 15–29, with a particular focus on students of the Faculty of Occupational Safety in Niš. The study examined respondents' understanding of the causes and consequences of climate change, perceptions of its impacts on human health and the environment, sources of climate-related information, and reported intentions to engage in environmentally responsible behaviour. The study also aimed to identify key areas relevant to climate education, environmental policy, and youth participation in environmental decision-making.

The demographic structure of the sample indicates a predominance of female respondents, who account for 64% of the total sample, compared to 36% male respondents. This reflects a higher representation of women within the surveyed population (Table 1).

Regarding age distribution, the largest proportion of respondents belongs to the 20–24 age group (43.33%) (Table 1). In terms of educational attainment, the majority of respondents have completed secondary education (71.33%) (Table 1). The sample is predominantly urban, with 82% of respondents reporting city residence (Table 1).

Table 1. Demographic structure of the sample

Gender structure	Male 36%
	Female 64%
Age structure	(15-19) 35.33%
	(20-24) 43.33%
	(25-29) 21.33%
Educational structure	High school 71.33%
	Academic studies 23.33%
	Master studies 4.67%
	Doctoral studies 0.67%
Place of residence	Village 18%
	City 82%

Source: Authors research

3. RESULTS

The study titled *Attitudes of Youth in Serbia on the Impact of Climate Change* was conducted by a research team from the Faculty of Occupational Safety in Niš, building on relevant international research, including studies implemented globally and in Southeastern Europe by the United Nations Development Programme (UNDP). The primary objective was to assess the extent to which climate change is present in the awareness of young people in Serbia.

In addition, the study provided a preliminary assessment of respondents' perceptions and awareness of climate change, including greenhouse gas emissions, perceived impacts on human health and the environment, recognition of key risk factors at both local and national levels, and expectations regarding Serbia's future development in the context of climate change.

The results indicate that a large proportion of respondents perceive climate change as a major problem, particularly at the global level (79.33%). Furthermore, higher levels of awareness regarding the impacts of climate change were observed among respondents aged 25–29 from urban areas, both at national and global levels (Figure 1).

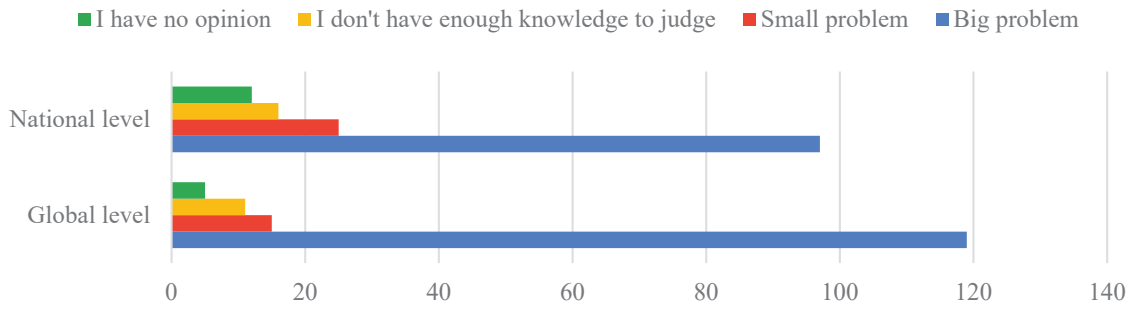


Figure 1. Evaluation of the effects of climate change on the national and global level (%)

The level of awareness of the consequences of climate change among respondents can be assessed as high, with values exceeding 70% across all indicators. The highest levels of familiarity were recorded for the impacts of climate change on plants and animals (95.33%) and on the increased frequency of extreme weather events and global warming (95.33%). Similarly, a high level of awareness was observed regarding impacts on agricultural production (94.66%). The lowest level of familiarity was recorded for soil erosion (76.66%) (Figure 2).

Differences in awareness were also observed across sociodemographic groups. Female respondents reported higher levels of familiarity with the consequences of climate change compared to male respondents. In addition, respondents aged 25–29 demonstrated greater awareness than those in the 15–19 and 20–24 age groups. When analysed by place of residence, respondents from urban areas showed higher levels of awareness compared to those from rural areas (Figure 2).

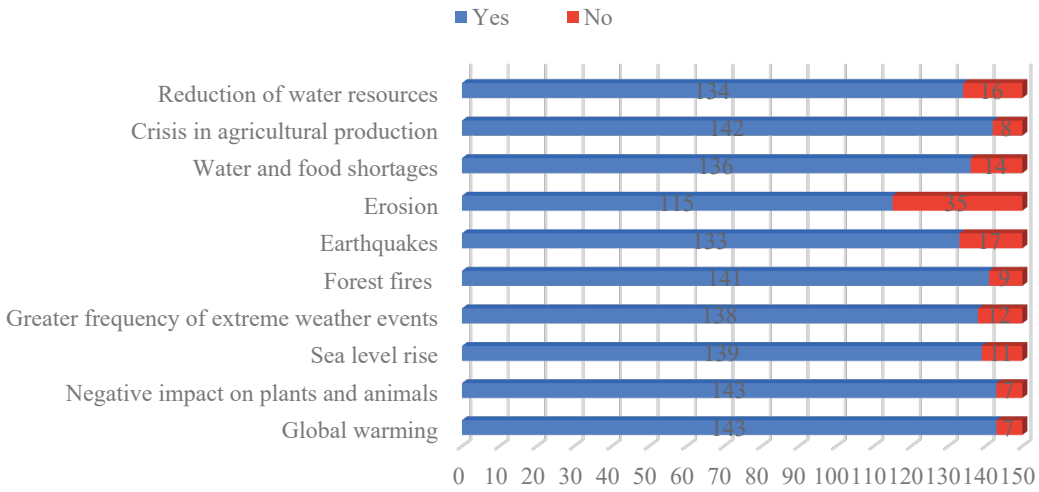


Figure 2. Knowledge about the consequences of climate change (%)

A total of 31.33% of respondents reported feeling concerned about climate change. Feelings of personal responsibility for environmental protection were reported by 22.67% of respondents. Smaller proportions of respondents indicated feeling interested (16.00%), powerless to change anything (10.67%), and scared (8.00%). Lower shares of respondents reported confusion (5.33%), disinterest (4.00%), and other responses (2.00%) (Table 2).

Table 2. How do you feel about climate change? (%)

Powerless to change anything	10.67%
Disinterested	4.00%
Responsible (protect the environment)	22.67%
Scared	8.00%
Concerned	31.33%
Interested	16.00%
Confused	5.33%
Other	2.00%

The results indicate that respondents most frequently identified industry (28.78%) and traffic and air pollution (24.37%) as the primary contributors to climate change. Waste was also identified as a significant factor (19.31%), while lower proportions of respondents attributed climate change to the

energy industry (9.97%) and the devastation of natural habitats (9.98%). Relatively few respondents identified agricultural production (3.45%), households (3.45%), or natural processes (1.84%) as major contributors to climate change (Table 3).

Table 3. What contributes most to climate change on scale of 1 to 100 (%)?

Natural process	1.84%
Agricultural production	3.45%
Waste	19.31%
Devastation of natural habitats	9.98%
Traffic and air pollution	24.37%
Households	3.45%
Energy industry	9.97%
Industry	28.78%

The results indicate that the majority of respondents (66.67%) believe that most young people in Serbia are not aware that their behaviour can influence climate change. A smaller proportion of respondents were unable to assess this issue (8.00%), while 13.33% believed that young people are not aware of this at all. Only 12.00% of respondents stated that most young people are aware that their behaviour can influence climate change (Table 4).

Table 4. Are young people in Serbia aware that they can influence climate change through their behaviour? (%)

I can not estimate	8.00%
I believe they are not aware of it at all	13.33%
I believe most are aware of it	12.00%
I believe most are not aware of it	66.67%

The results show that awareness of international climate policy frameworks is relatively low among respondents. A slight majority of respondents reported that they are not familiar with the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement (51.33%), while 48.67% stated that they are familiar with these agreements (Table 5).

Similarly, when asked about Serbia's commitments, as well as those of other countries under the Paris Agreement to reduce greenhouse gas emissions, 52.67% of respondents reported that they are not aware of these commitments, while 47.33% stated that they are aware of them (Table 6).

Table 5. *Ar*e you familiar with the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement (%)?

No	51.33%
Yes	48.67%

Table 6. Are you aware of the commitments that Serbia has made (as well as other countries that are signatories to the Paris Agreement) to reduce greenhouse gas emissions (%)?

No	52.67%
Yes	47.33%

The results indicate variation in self-reported levels of informedness about climate change. Nearly half of the respondents (48.00%) stated that they are well informed about the topic, while 12.00% considered themselves poorly informed. A notable proportion of respondents (31.33%) were unable to assess their level of informedness. A very small share (8.67%) reported that climate change is not a topic of interest to them (Table 7).

Table 7. Level of informedness about climate change (%)

I can not estimate	31.33%
It is not a topic that interests me	8.67%
Poorly informed	12.00%
Well informed	48.00%

The sources through which respondents obtain information about climate change are diverse, with the highest proportion reporting internet portals and websites (20.22%) as their primary source. Social networks represent the second most common source of information (19.39%). Science television channels account for 13.57% of responses, while 11.63% of respondents report learning about climate change during lectures at the faculty.

Informal communication also plays an important role, as 11.08% of respondents obtain information through conversations with friends, colleagues, and family. National and local television channels are reported by 8.86% of respondents, followed by YouTube (8.03%) and professional literature and scientific journals (7.20%) as the least frequently used sources of information (Figure 3).

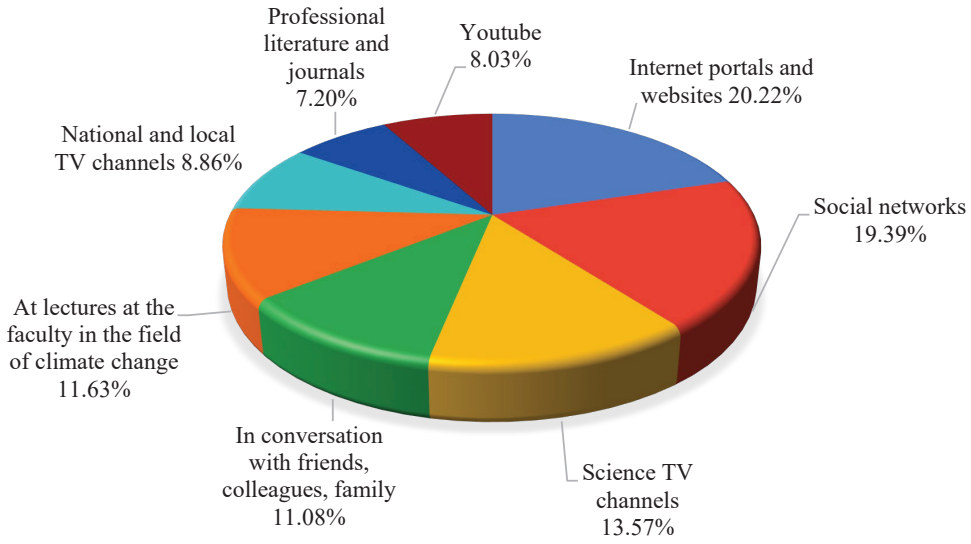


Figure 3. How do you get information about climate change? (%)

The results indicate a generally high willingness among respondents to learn more about climate change. The largest proportion of respondents (44.67%) stated that they would like to learn more if they believed they could contribute to reducing harmful environmental impacts. Furthermore, 28.00% of respondents reported that learning more about climate change is very important to them. Smaller proportions indicated conditional interest depending on relevance (11.33%), uncertainty in assessment (9.33%), and lack of interest (6.67%) (Table 8).

Table 8. Do you want to learn more about climate change? (%)

Yes, that is very important to me	28.00%
Yes, if you knew beforehand that it was important to me	11.33%
Yes, if I knew that I could contribute to the reduction harmful impacts	44.67%
I can not estimate	9.33%
No	6.67%

The survey results indicate that the largest proportion of respondents expressed an optimistic outlook regarding climate change in both the near and distant future, with optimism reported across both time horizons. (Figure 4).

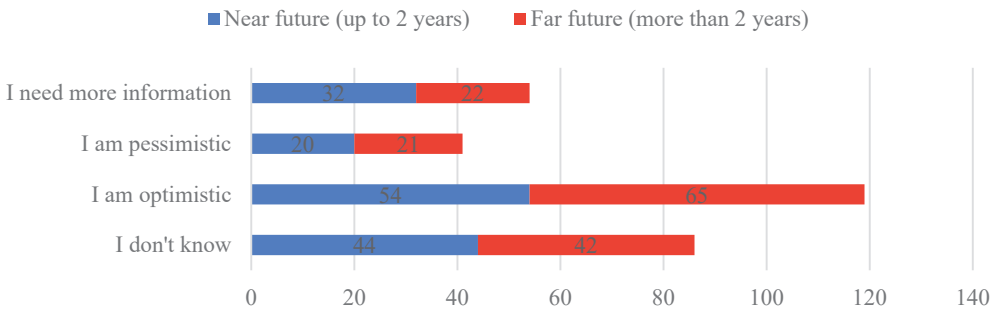


Figure 4. What are your feelings on climate change in the near and far future? (%)

The findings indicate a generally positive outlook, with optimism increasing from 36% in the near future to 43.3% in the far future. Pessimism remains relatively stable, accounting for 13.3% of respondents regarding the near future and 14% regarding the far future. Uncertainty is also notable, as 29.3% do not know what to expect in the near future, compared with 28% for the far future. Furthermore, the need for additional information decreases from 21.3% in the near future to 14.7% in the far future. Overall, the results suggest that respondents demonstrate greater confidence and a more positive perception when considering the far future (Figure 5).

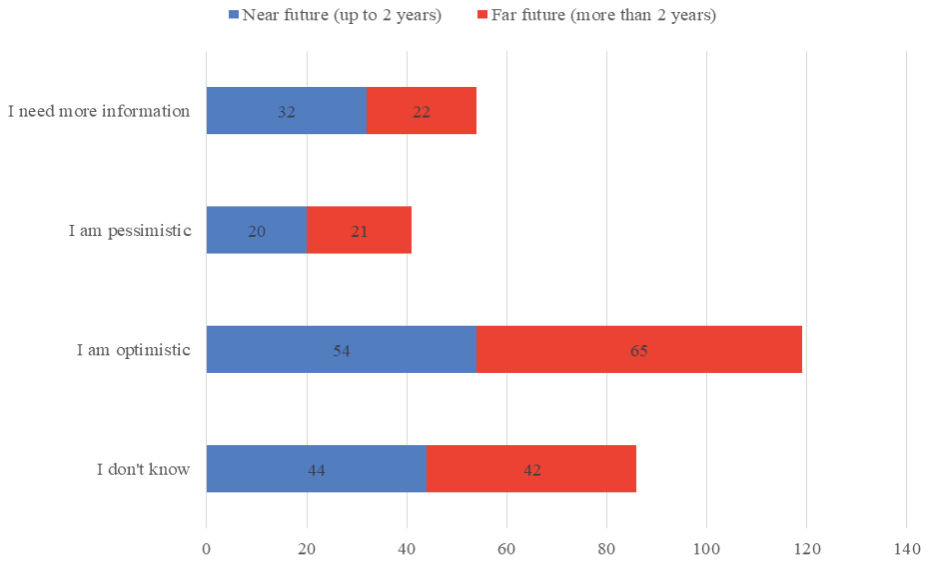


Figure 5. In the context of climate change, how do you view the near and far future? (%)

The results indicate that respondents perceive climate change impacts as highly differentiated across social and demographic groups. The majority of respondents believe that climate change has a large impact on people with impaired health (74.44%), people who work outdoors (72.78%), elderly people (69.44%), children (65.00%), and women (62.22%). A similarly high level of perceived impact is also reported for people of lower economic status (56.67%) and young people (59.44%).

Lower proportions of respondents attributed a large impact to men (56.67%) and people working in industry (51.11%). Across all categories, only a small share of respondents reported no impact or little impact, indicating a general perception that climate change disproportionately affects vulnerable population groups (Figure 6).

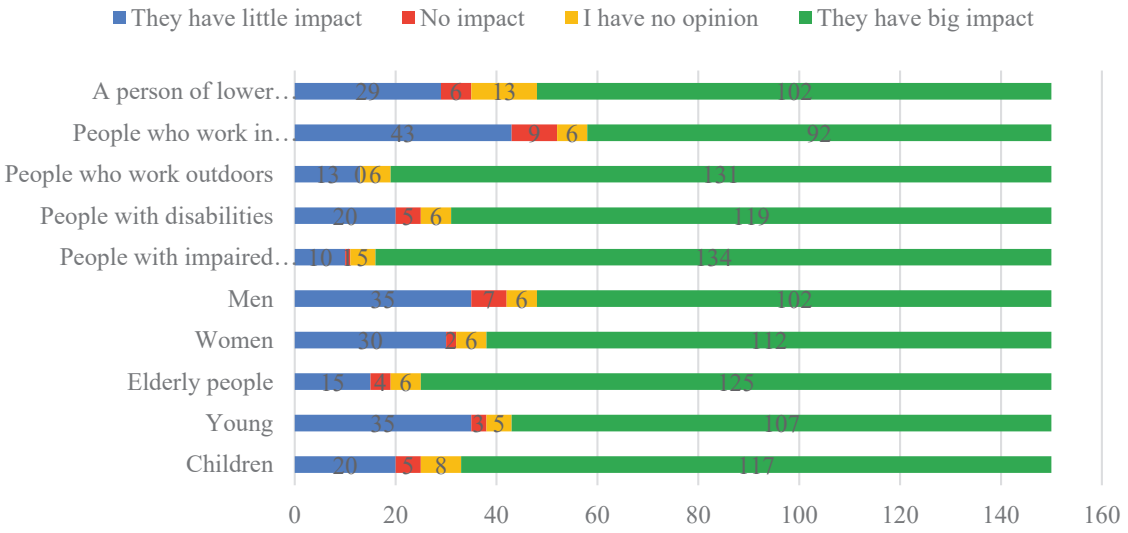


Figure 6. Impact of climate change on health and life (%)

The results presented in Table 9 show that respondents primarily attribute responsibility for addressing climate-change problems to the state and institutions responsible for establishing laws and regulations (88.66%). A substantial proportion also identified society and local communities (68.88%) as important actors. The private sector (50.00%) was identified by half of the respondents, while the international community (24.44%) and non-governmental organizations and associations (18.88%) were mentioned less frequently. Only 15.55% of respondents identified young people and 7.77% identified scientists as responsible. Overall, the findings indicate that respondents perceive climate-change mitigation primarily as an institutional and collective responsibility, with the state and local communities considered the most important actors. (Table 9).

Table 9. Do you want to learn more about climate change? (%)

Scientists	7.77%
Young people	15.55%
Non-governmental organizations, associations	18.88%
International community	24.44%
Private sector (companies, enterprises)	50.00%
Society and local community	68.88%
A contry with laws and regulations	88.66%

The results show a high willingness among respondents to change their lifestyle in order to reduce the negative environmental impact of human activities. The vast majority of respondents (83.33%) stated that they are willing to make such changes. A smaller proportion reported no opinion (12.00%), while only 4.67% of respondents stated that they are not willing to change their lifestyle (Table 10).

Table 10. Are you willing to change your lifestyle to reduce the negative impact of humans on the environment? (%)

Yes	83.33%
I have no opinion	12.00%
No	4.67%

4. DISCUSSIONS

The findings of this study are broadly consistent with previous research showing that young people tend to demonstrate a relatively high level of awareness of environmental and climate-related problems. Previous studies conducted in Serbia and other European countries have reported similar patterns, indicating that young people generally recognize the importance of environmental protection and express willingness to contribute to reducing environmental harm [11–18]. The high level of awareness observed among the respondents in this study may partly reflect the increasing visibility of climate-related events, environmental issues in public discourse, and the growing availability of information through digital and social media.

The results are also consistent with Ančić et al. [4], who found that greater awareness and concern about environmental problems are associated with greater willingness to accept personal sacrifices for environmental protection. In the present study, respondents similarly demonstrated awareness of the consequences of climate change and a general readiness to modify their behaviour. However, the findings also indicate that awareness alone may not be sufficient to ensure sustained individual action. This may be explained by the influence of social norms, perceived individual efficacy, access to environmentally friendly alternatives, and the extent to which respondents perceive environmental protection as an individual rather than a collective responsibility.

The respondents' tendency to attribute substantial responsibility for addressing climate change to the state, local communities, and other institutions is particularly relevant in this context. This finding may indicate that young people perceive climate change primarily as a systemic problem requiring institutional solutions rather than solely as a matter of individual behaviour. Such an interpretation is compatible with previous research emphasizing the role of broader social values, institutional conditions, and political context in shaping environmental attitudes [8–10]. At the same time, assigning responsibility to institutions does not necessarily exclude individual responsibility; rather, it may reflect an expectation that appropriate policies and infrastructure should support environmentally responsible choices.

The findings concerning young people's willingness to learn more about climate change are also important when considered in relation to the role of education. Previous studies have identified education as one of the more consistent factors associated with environmental awareness and engagement [4–7]. In Serbia, climate-related topics are generally incorporated into broader environmental and sustainability content within the formal education system rather than taught as

a separate compulsory subject. The respondents' interest in acquiring additional knowledge may therefore indicate the potential value of strengthening and expanding climate-related content within existing educational programmes. At the same time, education should not be limited to increasing factual knowledge, but should also provide opportunities for practical engagement and participation.

The reliance on contemporary media as a major source of information may also help explain the relatively high level of awareness observed in the study. Young people are among the most frequent users of digital communication channels, which provide rapid access to information about climate-related events and environmental issues. However, digital media also contain information of varying quality and reliability. Consequently, greater exposure to climate-related content does not necessarily guarantee a deeper or scientifically accurate understanding of the issue. Educational institutions may therefore play an important role in helping students critically evaluate climate-related information and distinguish evidence-based information from misinformation.

The present findings should also be considered in relation to previous research showing differences in environmental attitudes according to gender and education [11,12,14,19–21]. Although the present study provides useful evidence on the surveyed student population, the non-representative sample and its specific educational context limit the extent to which these patterns can be compared with or generalized to the wider youth population in Serbia. Future studies should therefore investigate whether demographic characteristics, educational background, access to information, and previous environmental engagement significantly influence climate-change awareness and behavioural intentions.

Overall, the findings support the broader literature indicating that young people generally recognize climate change as an important environmental and social issue. However, the results also suggest that a potential gap remains between awareness, willingness to act, and actual environmental behaviour. This gap may be influenced not only by individual knowledge and attitudes but also by educational opportunities, social norms, institutional support, and the availability of practical opportunities for sustainable behaviour. Strengthening climate education and creating meaningful opportunities for young people to participate in environmental initiatives may therefore help translate existing awareness into more consistent and sustained environmental action.

5. CONCLUSION

The analysis of the study *Attitudes of Youth in Serbia on the Impact of Climate Change* indicates a generally high level of awareness regarding climate change and its associated impacts among the surveyed population.

Climate change is predominantly identified as a global-scale issue, with a substantial proportion of respondents also acknowledging its national relevance. Reported levels of awareness regarding climate change consequences are elevated, particularly in relation to ecological systems, including biodiversity degradation, impacts on flora and fauna, and increased frequency of extreme weather events.

The perceived drivers of climate change are primarily attributed to industrial activities, transport emissions, and inadequate waste management systems. At the same time, results indicate a partial deficit in the recognition of the relationship between individual behavioural patterns and climate change processes, as a non-negligible proportion of respondents does not associate personal behaviour with climate change impacts.

Knowledge of institutional and policy frameworks is present, including awareness of the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement, and related national obligations. Self-assessed levels of informedness are predominantly moderate to high, with information acquisition primarily associated with digital media platforms (internet and social networks) and formal educational settings.

Variations in awareness are observable across sociodemographic categories, with higher levels of knowledge and engagement recorded among female respondents and older age groups. Climate change is widely perceived as having significant implications for human health and quality of life, particularly for vulnerable population groups. Responsibility for addressing climate change is predominantly attributed to state-level actors.

Given the non-representative nature of the sample, generalization of the findings to the wider youth population in Serbia is limited. Nevertheless, the results provide empirically grounded insights into patterns of awareness, perception, and behavioural orientation related to climate change among the surveyed cohort.

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Professional paper

MARINE WASTE MANAGEMENT A PREREQUISITE FOR A HEALTHY LIFE AND ENVIRONMENT

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Abstract: *Marine waste represents a significant problem of environmental protection and sustainable development. The paper presents the problems caused by the impact of marine waste on the environment, on marine organisms, and indirectly on human health. Microplastics and nanoplastics serve as carriers of various potential hazards, such as toxic additives, pathogenic microorganisms and antibiotic resistance genes. There is more and more research showing that air, food and water are contaminated with microplastics and that people can inhale or swallow them. Many initiatives, recommendations and laws are adopted at the global, regional and national level in order to reduce the amount of plastic in the sea to an acceptable level. New technologies, new methods of data collection and many preventive activities are used in order to reduce the use of plastic materials and raise the awareness of the population about the danger of accumulating marine pollution. –*

Keywords*: marine waste, plastic, marine organisms, sustainable development, human health*

1. INTRODUCTION

In the world's seas and oceans, about ten million tons of waste end up annually. Most often, it is plastic waste, which not only remains in the environment for a very long time, but also has a continuous harmful effect on it. Namely, plastic that is present in open seas and coastal areas causes financial losses, endangers the health of animal and plant life, and thus directly and indirectly has a negative effect on human health and the economy. [1]

Marine organisms in interactions with plastics most often swallow smaller pieces and get entangled in larger pieces of plastic. Plastic interactions have been documented for nearly seven hundred different marine species, and marine turtles are among the most endangered species. Scientists have proven that all seven known species of turtles are seriously threatened by the negative impact of plastic. [2]

There is growing research showing that air, food and water are contaminated with microplastics and that people can breathe or swallow. According to current knowledge, the nature of the risk

depends on the physical characteristics and chemical composition, as well as the time of biological degradation. Microplastics serve as a carrier of various potential hazards, such as toxic additives, pathogenic microorganisms, and antibiotic resistance genes.[3] However, the actual concentrations of inhaled and swallowed microplastics that accumulate in the human body are not yet known. Further research in this area is certainly needed to obtain more specific answers. The potential effects of microplastics on human health can be divided into three main categories: chemical, physical and biological effects, and then further according to exposures and possible clinical effects.

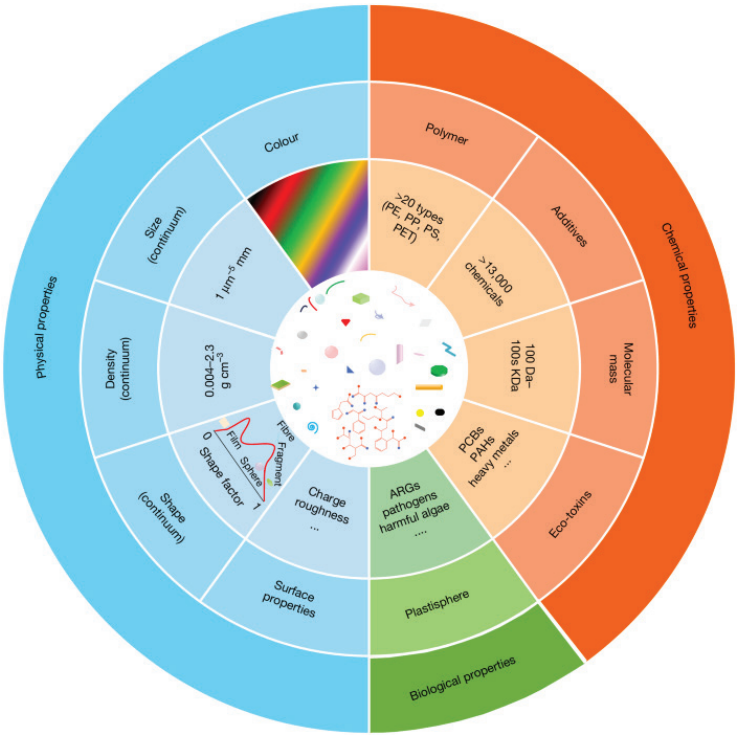
2. PLASTIC, MICROPLASTICS, NANOPLASTICS

Plastics are complex synthetic compounds made from carbon-based materials, encompassing a variety of polymers, shapes, additives, and levels of degradation. Most plastics are derived from fossil fuels and other fossil materials, although they can also be made from other sources, which in some case is a type of biodegradable plastic.

As the human population grows, so does the production of plastics, as evidenced by the fact that global plastic production has increased from 1.5 million tons in the 1950s to 359 million tons in 2018. In 2022., 400.3 million tons of plastic were produced. [4] The microplastics produced are also used commercially in scrubs, cosmetics, pharmaceuticals, food and synthetic textiles, which also end up in the environment.

Plastic pollution has become a global problem. Legislation and waste management initially focused on macroplastics because they are visible to the eye and were a priority. Various laws prohibit the improper disposal of plastics in the environment, but more recently, more attention has been paid to microplastics. However, there are still no specific laws that regulate the amount of microplastics allowed in the environment. People are not yet aware that by dumping plastic into the environment, they are actually damaging their health. Most waste found in nature, including plastic, enters a continuous cycle. [5] Once in nature, plastic undergoes various degradation processes and is broken down, creating microplastics that organisms such as fish take into the food chain and ultimately end up in the human body. Plastics are slowly broken down by microorganisms, heat, oxidation, light or water. When plastic breaks down, it forms microplastic and submicron nanoplastic particles in all shapes, chemical compositions, sizes and concentrations.

Microplastics vary in physical (size, shape, density, surface properties), chemical (polymer type, additives, molecular structure, adsorbed chemicals), and biological (plastic-associated microbiome, the ‘plastisphere’) properties. These factors, shaped by manufacturing and environmental influences, complicate the measurements of microplastics and influence their ecological impact: ARGs, antibiotic-resistant genes; PAHs, polycyclic aromatic hydrocarbons; PCBs, polychlorinated biphenyls; PE, polyethylene; PP, polypropylene; PS, polystyrene; PET, polyethylene terephthalate.



– figure 1. [6]

Figure 1: Microplastic – Physical, Chemical and Biological properties

3. WASTE IN THE OCEANS, MEDITERRANEAN, ADRIATIC

Plastics and microplastics are the main components of marine waste – they account for about 60-80%, in some areas even up to 95%. Microplastics are a very harmful form of plastic and, due to their toxic properties, they impair the health of all living organisms. [7] In addition, they are very good adsorbents and bind most of the harmful substances that are found in their vicinity, which makes them even more harmful to living organisms. The largest quantities of microplastics can be found in the seas and oceans. [8] Research shows that about 8 million tons of microplastics are released into the oceans every year. It is assumed that by 2050 there will be more plastic than fish in the seas and oceans. [9,10,11]

Today, plastic products account for 95 percent of the waste floating in the Mediterranean Sea or lying on beaches. Most of the plastic waste in the sea comes from Turkey and Spain, followed by Italy, Egypt and France. Due to increased tourism, the amount of marine waste increases by as much as 40 percent every summer. [6]

According to the quantity and presence of plastic waste, the Adriatic Sea is the most polluted in Europe after the northeastern part of the Mediterranean and the Celtic Sea. Research has shown that extremely high concentrations of microplastics have been detected in the northern Adriatic (Gulf of Trieste), with an average value of about 406,000 particles/km2, which is among the highest concentrations recorded in the Mediterranean Sea to date. [12,13,14,15]

Waste enters the Adriatic Sea from about four million people living along its coasts, but this number increases almost sixfold during the tourist season. The waste generated is also a consequence of coastal industries, as well as intensive shipping traffic and the sea current regime. On the beaches and seabed of the coastal area of Croatia, marine waste is present in quantities that are not negligible. Large quantities of waste are brought to the Croatian coast by sea currents and wind from neighboring Adriatic countries (Albania, Italy), especially during exceptionally unfavorable meteorological and hydrological conditions. The Croatian coast is additionally polluted by yachts and passenger ships, with their increasing number and frequency of visits. The composition and distribution of waste suggests that mainly tourism and public activities are the main culprits for pollution in Adriatic waters. [15,16,17]

4. HARMFUL IMPACT ON MARINE HABITATS AND ANIMAL

The sea has a major function for the entire ecosystem and is a habitat for numerous marine organisms and an important factor in the survival of humanity. Large amounts of plastic waste threaten the marine ecosystem and lead to the injury and death of many wild, strictly protected marine animals such as marine mammals and turtles and many species of fish.

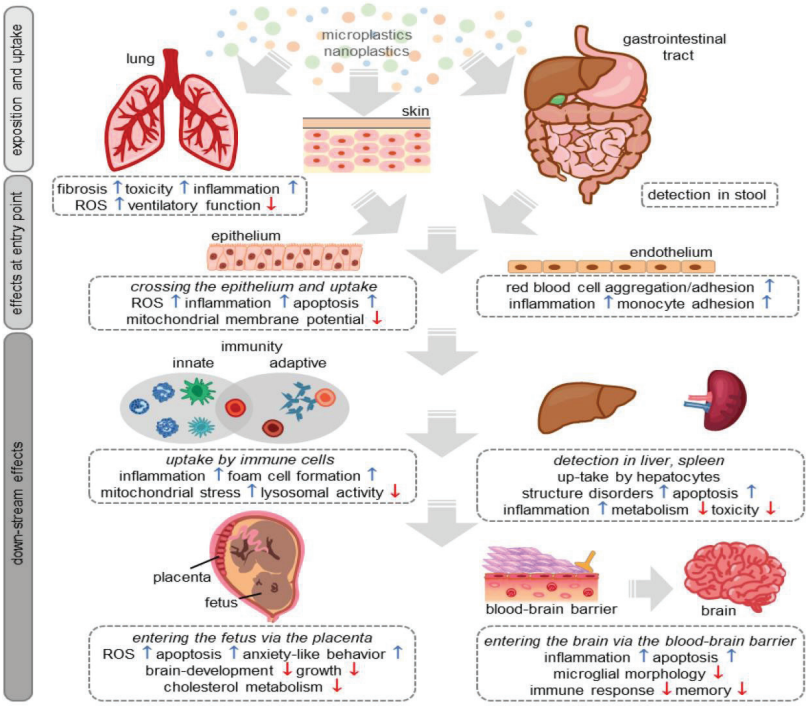
Microplastic particles, although small in diameter, have a large active surface area and bind numerous pollutants, which contributes to their toxicity. [2] Heavy metals, pathogens and organic pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and pesticides are adsorbed onto the surface of microplastics. [18,19] It is precisely because of the above properties that they pose a great danger to the environment and living organisms. Microplastics, when passing through organisms, cause various biological effects, such as metabolic disorders, oxidative stress, immunological, neurological and histological damage, and DNA damage. Fish often mistake plastic for food. [1] UN estimates indicate that about 30% of fish contain microplastic particles in their tissues, which affect the ability of marine organisms to reproduce, their ability to catch prey, bone fragility, longer search for prey, and more.

5. POTENTIAL EFFECTS ON HUMAN HEALTH

In addition to food, microplastic particles can reach the human body through various routes. Today, much research is being conducted on the impact of plastics on the human body. A number of projects and studies are being conducted to investigate the impact of plastics on humans. [6]

Figure 2. shows a flow chart to illustrate the possible effects of microplastics on human health. The dashed lines represent current research.

Little is known about how plastics affect human health. Chemicals in mixed plastics enter each other, creating the so-called “cocktail effect” that enters the human body when consumed. Some chemicals affect the endocrine system – bisphenols, phthalates, etc. The EU Food Safety Agency estimates that the amount of bisphenol A should be 100,000 times lower than before. Microplastics have been found in many human organs – lungs, spleen, kidneys, skin, gastrointestinal tract,



placenta, liver, brain, or bloodstream. [20] Some chemicals can cause cancer, affect the circulatory system, immune system, brain, reproductive system or diabetes. – figure 2.

Figure 2. shows the effects of microplastics on individual organs.

6. CONCLUSION

WORLD WILDLIFE FUND (WWF) indicates the dramatic consequences that excessive plastic use, poor waste management and mass tourism have on one of the most visited regions in the world – Mediterranean region. By gathering the latest data and scientific evidence on the use of plastics in Europe and many ways how plastics affect marine ecosystems, the report presents an exhaustive roadmap for urgent measures that institutions, companies and citizens must take to prevent plastic waste from reaching the sea. Large plastic parts injure, choke, and often kill marine animals, including protected and endangered species such as sea turtles and the Mediterranean monk seal. But it was microplastics, smaller and more insidious, that reached record levels of concentration of 1.25 million pieces per square kilometer in the Mediterranean Sea, almost four times more than on the "plastic island" found in the North Pacific Ocean. By entering the food chain, fragments of microplastics threaten an increasing number of animal species, as well as humans. According to the report, delays and “holes” in plastic waste management in most countries are among the main causes of plastic pollution. Of the 27 million tonnes of plastic waste produced each year in Europe only one-third are recycled; half of plastic waste in Italy, France and Spain ends up in landfills.

WWF calls on governments, businesses and individuals to adopt a number of measures to reduce plastic waste pollution in urban, coastal and marine environments globally. **This includes**: the adoption of a legally binding international agreement to remove plastic waste from the sea, supported by strong national targets to achieve 100 percent recycled and renewable plastic waste by 2030, and national bans on single-use plastic items such as bags. invite companies to invest in innovation

and design in the direction of more efficient and sustainable use of plastics. Plastic pollution is too big a problem to be solved by only one continent, one government or one industrial sector. Only by working together can we free our oceans, seas, rivers, cities and lives from unnecessary plastics,

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Professional paper

THE ŠAGULJE REGIONAL WASTE MANAGEMENT CENTER: A STRATEGIC PILLAR FOR REGIONAL SUSTAINABLE DEVELOPMENT

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Abstract: *Establishing regional waste management centers (WMCs) is imperative for Croatia's alignment with the EU's circular economy goals. This paper explores the role of the WMC Šagulje – a key strategic infrastructure for the Brod-Posavina region. The introduction provides a summary of the existing European legislative framework and a comparative analysis of waste management systems. The analysis includes spatial characteristics and evaluates the advantages and challenges of an integrated waste management system. The central part deals with the technical and technological structure of the WMC Šagulje and its contribution to regional development. Taking into account the impact on the socio-economic affordability of service pricing for end-users, particular focus is placed on examining mixed municipal waste flows, projecting landfill reduction, and assessing economic sustainability. The paper provides recommendations for optimizing operational processes. The aim is to provide insight into the significance of the WMC Šagulje as indispensable infrastructure for fulfilling national goals and ensuring long-term ecological and economic sustainability within the observed area.*

Keywords: *circular economy, sustainable regional development, Šagulje, waste management*

1. INTRODUCTION

Waste management is important in modern societies due to the increasing challenge of growing quantities of municipal waste, which is a result of greater pressures on the environment. With the development of societies, economic development and globalization, anthropogenic impact on the environment is such that countries have recognized the importance and need for stricter environmental protection requirements. In the Republic of Croatia (RH), the waste management system has been developing in recent years towards the establishment of integrated regional waste management centers, which should ensure more efficient, economically sustainable and environmentally acceptable waste management. In this context, the Šagulje Waste Management Center (RCGO)

project represents a strategic infrastructure project of regional importance, the implementation of which has the potential to significantly improve the existing system in Brod-Posavina County (BPŽ) and wider coverage.

The research problem arises from the insufficiently efficient existing waste management system, which in many parts of the observed area still relies to a significant extent on waste disposal as the dominant method of disposal. Such an approach leads to limited use of resources contained in waste, increased environmental burden and the need to close and rehabilitate existing landfills. In addition, the fragmentation of the system and uneven infrastructure between local government units make it difficult to achieve the goals defined by European and national waste management policies. In this context, there is a need to analyze the role and significance of a regional waste management center as a possible solution to existing structural problems.

A combined methodological approach was applied in the preparation of the paper, which includes an analysis of relevant professional and scientific literature, a review of legal and strategic documents in the field of waste management, and an analysis of available planning and project data related to the

RCGO Šagulje. A descriptive method was used to present the existing system and planned solutions, a comparative analysis to compare with European and national frameworks, and a synthesis method to connect theoretical knowledge and practical aspects of project implementation. Special emphasis was placed on the interpretation of data from planning documents and their role in assessing the strategic significance of the project.

Waste is any object or material that its owner discards, plans to discard or is required to dispose of by applicable regulations [1]. Given the continuous generation of waste as a result of various human activities, it is necessary to establish an appropriate waste management system in order to reduce its negative effects on the environment and human health. Waste management encompasses a set of activities related to the collection, transport, recovery and final disposal of waste, where recovery also includes waste sorting procedures. In addition to the operational procedures themselves, waste management involves the implementation of supervision over their execution, as well as the control and application of appropriate measures at locations where waste is disposed of or has previously been disposed of [2].

One of the most important environmental challenges in RH is waste management. Waste management used to be based on collection and disposal, without a significant share of recycling or separate collection. Such practices were present in a large part of the population, and waste reuse and recovery systems were poorly developed [3].

In an effort to achieve the goals of sustainable waste management and fulfill the obligations assumed by national and European regulations, the concept of waste management centers (WMCs) has been developed in the RH. These are complex infrastructure systems that play a key role in modernizing waste management, reducing the amount of waste ending up in landfills, and increasing recycling rates.

2. LEGISLATIVE FRAMEWORK

Effective waste management is not possible without a clearly defined legislative and institutional framework that determines the rights, obligations and responsibilities of all participants involved in the system. Legal regulations play a key role in guiding activities related to the prevention of waste generation, its collection, treatment, recovery and disposal, while protecting the environment and human health. Since the area of waste management is regulated at the European Union (EU) level, Member States are obliged to harmonize their national legislation with European directives and sustainable development goals.

Waste management policy in the EU is characterized by continuous development, with a gradual transition from traditional waste disposal to a circular economy model. The fundamental objective of such an approach is to reduce waste generation to a minimum and to ensure that materials and products remain in the economic system for as long as possible after use through reuse, recycling and other recovery processes. This approach aims to reduce the burden on the environment, conserve natural resources and increase the efficiency of raw material use [4].

Today, the basis of the EU legislative framework in the field of waste management is the Waste Framework Directive (WFD) [5]. Its main objective is to ensure a high level of environmental and human health protection through measures aimed at preventing the generation of waste, reducing its negative impacts and improving the way waste is handled. At the same time, the directive promotes a more rational use of natural resources and supports the transition to a circular economy model, which is one of the key development goals of the EU [5]. The Constitution, as the fundamental legal act of the RH, stipulates in Article 3 that “the preservation of nature and the human environment are one of the highest values of the constitutional order of the RH”, and in Article 70 it stipulates that “every person has the right to a healthy life, that the state ensures conditions for a healthy environment and that everyone is obliged to pay particular attention to the protection of human health, nature and the human environment” [6].

A significant step forward was achieved with the adoption of the Waste Management Plan (WMP) of the RH for the period 2017–2022, which brought the RH system more closely into line with the EU concept of the waste hierarchy [7]. Further development of the system is defined by the WMP of the RH for the period 2023–2028, adopted in June 2023. The new plan defines goals aligned with EU directives and directed towards the circular economy [8]. The Environmental Protection and Energy Efficiency Fund (FZOEU) deals with the financing of all environmental protection activities. This institution is necessary for collecting and channeling financial resources into projects and programs aimed at preserving the environment, protecting nature and increasing energy efficiency [9].

3. RESULTS AND DISCUSSION

The area of Slavonian Posavlje is today home to the BPŽ (Fig. 1), which covers an area of 2,034 km², or approximately 3.6% of the total area of the RH [10]. Overall, there are 185 settlements in the BPŽ, and according to the 2021 Census, the county had 130,267 inhabitants [11]. In 2024, a total of 28,511 tons of municipal waste were collected in the BPŽ [12].

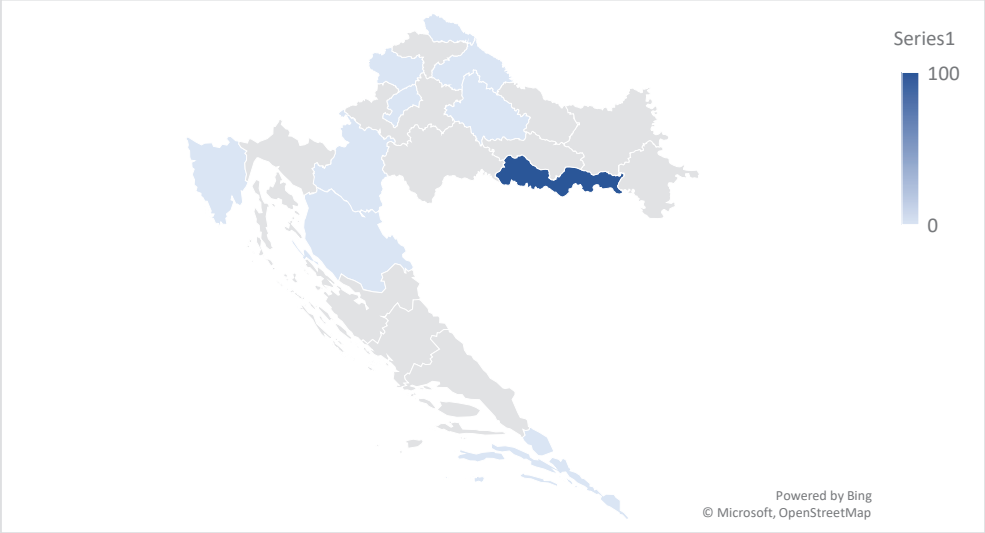


Figure 1. Geographical location of Brodsko-Posavska County (marked in dark blue).

Source: author's creation

According to Fig. 2, public utility services collect 94% (26,922 tons) of the total waste, which is predominantly comprised of mixed municipal waste at 62.4%. Furthermore, the data reveals that while the majority of public service waste is collected directly by providers, a smaller portion of 928 tons is received through recycling centers [12].

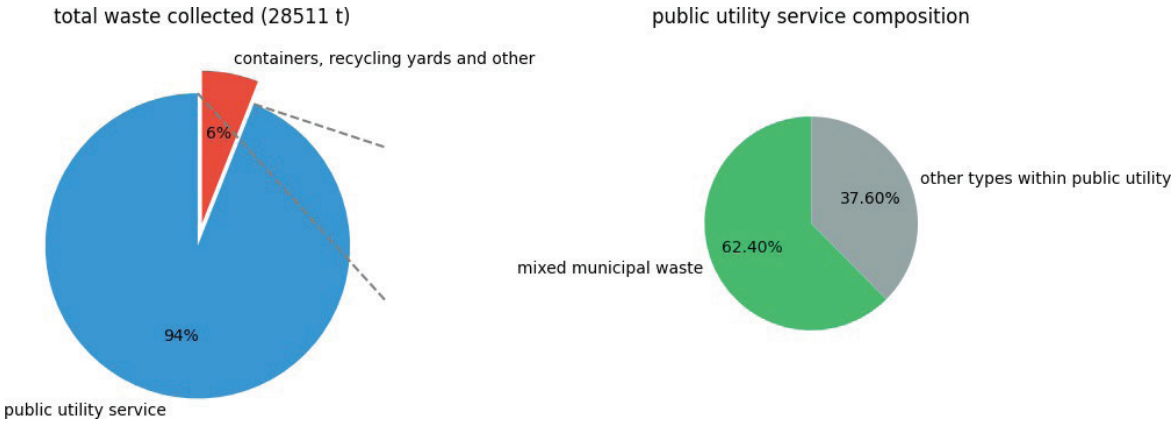


Figure 2. Structure of Collected Waste and Share of Mixed Municipal Waste

Source: author's creation according to [12]; Python by author in Google Colab

As illustrated in Fig. 3, the separate waste collection rate experienced significant growth between 2021 and 2024, increasing from 21.7% to 37.6%. Regarding waste treatment, it can be concluded from the above that waste disposal still remains the primary method [12].

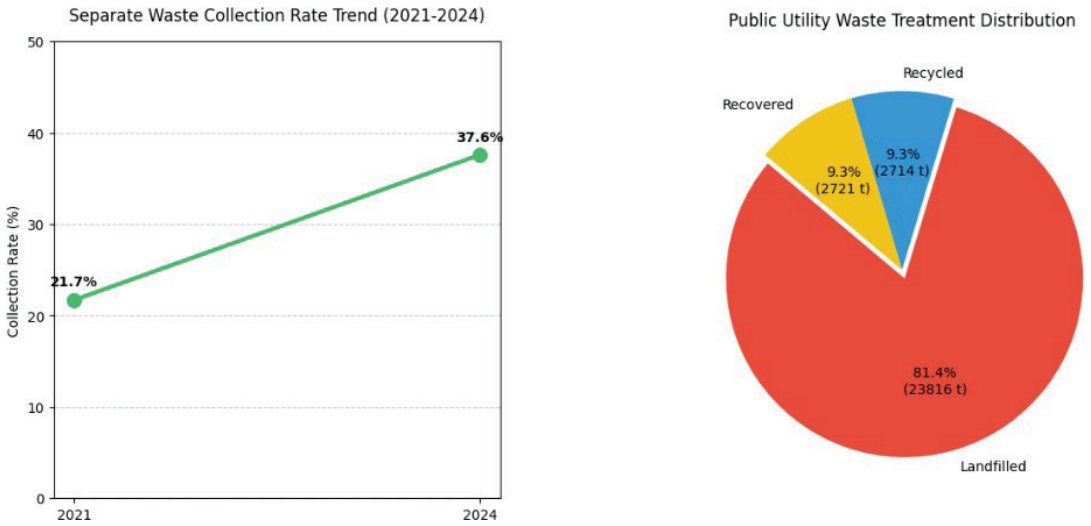


Figure 3. Municipal Waste Management: Separation Trends and Treatment Overview

Source: author's creation according to [12]; Python by author in Google Colab

The separate municipal waste collection system in the BPŽ is organized through the activities of six public service providers who, based on contracts concluded with local government units, ensure the implementation of the public waste collection service and related activities. The service has been established in the territory of all 28 local government units, thus achieving territorial coverage and accessibility of the system to all users [13].

As part of the development of a modern waste management system in the BPŽ, the construction of the RCGO Šagulje is planned, which represents a key infrastructure project for the establishment of comprehensive and sustainable municipal waste management. The project is envisaged in the WMP of the BPŽ for the period 2024–2029 and is designed as a central facility for waste treatment and disposal in the wider regional area [13].

The significance of the project goes beyond the administrative borders of the county itself, as the RCGO Šagulje will serve as a regional waste treatment center for the Brod-Posavina, Požega-Slavonia and Virovitica-Podravina counties, as well as part of Sisak-Moslavina County. This will establish an integrated waste management system covering a large number of local government units, enabling more efficient use of infrastructure, cost rationalization and alignment with national and European circular economy goals [13].

The project includes not only the construction of a new waste management center, but also a series of accompanying activities aimed at improving the existing system. This includes the closure of existing landfills after the center is operational, the continuation of remediation measures at active and closed landfills, the removal of illegal landfills and the remediation of sites contaminated by improperly disposed waste. In this way, the project contributes to reducing negative environmental impacts and increasing the level of protection of soil, water and air [13].

Given the complexity of the system, the spatial coverage of the center is organized into fourteen functional zones. These include the entrance-exit area, the administration building, the transportation center, storage facilities, a waste recycling and recovery facility, leachate and landfill gas treatment systems, energy facilities, landfills, construction waste treatment facilities, and transport and utility infrastructure. Such an organization allows for optimal material flow and efficient management of all processes within the center [13].

The planned capacities of the center are in line with the regional volume and anticipated activities. The landfill for non-hazardous waste is designed for a total capacity of approximately 1.2 million m³ of waste, while the planned capacity for inert waste is approximately 560,000 m³. A construction waste recycling plant with a capacity of approximately 7.9 tons per hour is planned within the center [13].

Fig. 4 provides a detailed insight into the locations, showing the exact spatial layout that should ensure optimized logistics flow between the transport hub, processing units and the administrative sector. Similar to operational RH waste management centers (CGO) like Bikarac and Biljane Donje, the Šagulje facility relies on an integrated mechanical-biological treatment (MBT) concept, but distinguishes itself by incorporating a large-scale photovoltaic plant for clean energy production. While centers like Marišćina and Kaštijun were among the first to become fully operational in RH, RCGO Šagulje represents part of the newer, strategically planned generation of regional centers designed to simultaneously service multiple counties through an optimized network of transfer stations.

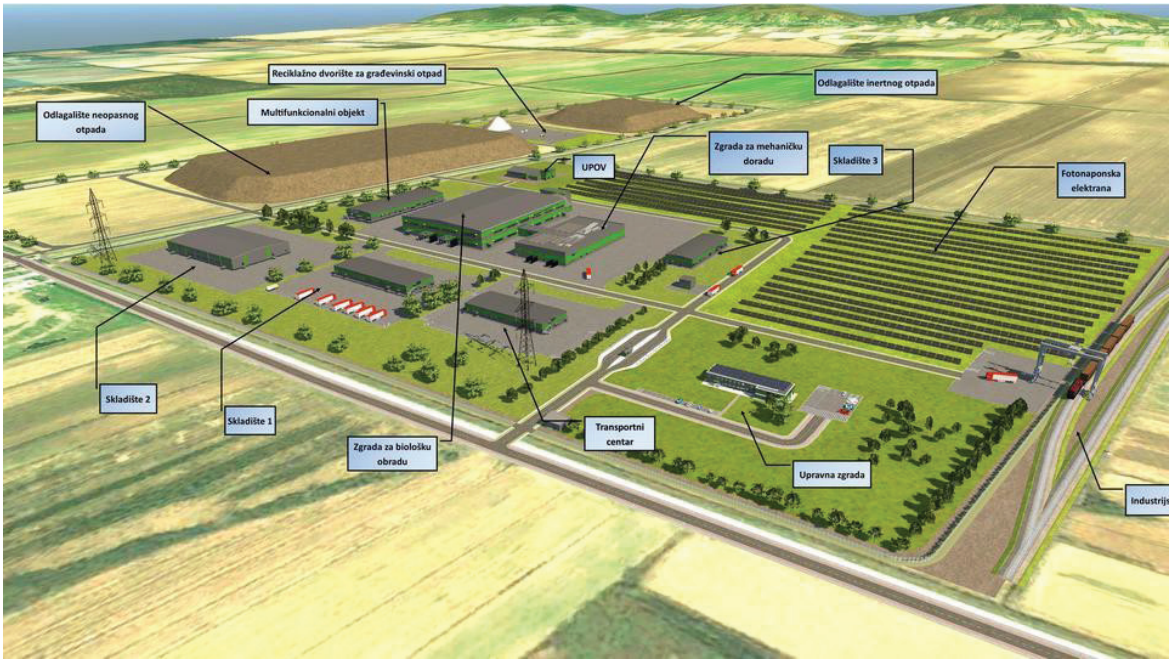


Figure 4. Schematic layout of the Šagulje Waste Management Center (WMC) facilities

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4. CONCLUSION

Based on the above, it can be concluded that the Regional Waste Management Center (RCGO) Šagulje is an extremely important milestone in the modernization of waste management infrastructure in the Brod-Posavina County and beyond, which is especially significant for a large part of Pannonian Croatia according to the NUTS 2 region. The results of this work confirm the achieved positive trend in separate waste collection, which recorded a stable growth of 16% over a period of 4 years, which speaks in favor of the increasing strengthening of the source separation system.

However, the analysis also reveals a serious systemic challenge: a dominant 88.5% of public service waste still ends up in landfills, while recycling and recovery rates are limited to around 10.1%. By integrating several counties—Brodsko-Posaviska, Požega-Slavonska, Virovitica-Podravina and part of Sisak-Moslavina counties—RCGO Šagulje brings much-needed infrastructure that relies on a modern concept of mechanical-biological treatment (MBT) with the production of clean energy through its own photovoltaic power plant. The main relevance and usefulness of this paper is evident in providing an analytical framework that connects existing structural shortcomings, such as system fragmentation and reliance on waste disposal, with practical large-scale solutions needed to meet national goals and strict European Union directives on the circular economy.

In conclusion, ensuring the long-term environmental and economic sustainability of this area requires continuous monitoring and targeted future activities. Future research and operational monitoring should focus on the socio-economic affordability of the service prices for end-users in order to maintain a high rate of citizen participation in waste separation. It is also necessary to precisely monitor the flows of mixed municipal waste in order to measure the projected reduction in the quantities ending up in landfills once the center becomes fully operational. Ultimately, a successful transition to a circular economy model will depend on the optimization of operational processes, along with the expansion of local recycling infrastructure. It would certainly be good to organize and implement educational programs for citizens. The chosen example of RCGO is excellent because it provides insight into the results of cooperation between the EU, the government of the Republic of Croatia and local authorities in practice, with the aim of protecting the environment and ensuring the quality of life of all citizens, regardless of the region they come from.

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Original scientific paper

ANALYSIS OF SOME POSSIBILITIES OF USING HEAT PUMPS IN PRODUCTION DECARBONIZATION PROCESSES

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Abstract: *This paper analyses the application of heat pumps in a milk pasteurization plant, focusing on reducing fossil fuel use and CO_2 emissions. Conventional pasteurization systems rely on natural-gas-fired steam boilers and therefore have a considerable carbon footprint. As an alternative, a heat pump system is considered to simultaneously heat and cool milk streams within the process. A detailed thermodynamic model of a single-stage heat pump was developed to evaluate coefficients of performance, heat exchanger heat flows, and optimal operating conditions for different working fluids. Exergy analysis was used to quantify losses and identify the components with the highest exergy destruction. The economic analysis included capital cost estimation, operating costs, and payback period calculation. Environmental performance was assessed by comparing CO_2 emissions of the conventional and heat-pump-based systems. The results show that heat pumps can significantly reduce greenhouse gas emissions with an acceptable payback period. Ammonia proved to be the most favourable working fluid, providing the best thermodynamic and ecological performance. The study confirms that heat pumps are a sustainable technical and economic solution for decarbonizing the dairy industry.*

Keywords: *heat pump, thermodynamic analysis, economic analysis, milk pasteurization, decarbonization*

1. INTRODUCTION

Decarbonizing milk pasteurization process in dairy industry requires transitioning from fossil-fuel-fired steam boilers to electrified thermal systems, especially including implementing industrial heat pumps. Figure 1. a) shows a schematic representation of a pasteurization plant, where standardized pasteurized milk with 3% fat is produced from raw milk with 3.6% fat. The plant consists of six plate heat exchangers (from HE1 to HE5 and PHE), two pumps (P6 and P7) and a holding tube (HT), and

a plant for technological processing of raw milk. The main objective of the pasteurization process is to heat standardized milk with 3% fat using hot water to 80°C (state 26 in Figure 1.a)), hold it for a sufficient time in the holding tube (HT), after which it needs to be cooled to a storage temperature of 4°C with ice water. Therefore, in the milk pasteurization plant, for the pasteurization process to take place, it is necessary to ensure a flow of ice water for cooling the milk and a flow of hot water (temperature 85°C) for heating the milk streams. In today's dairy industry plants, ice water is produced using ammonia (NH_3) refrigeration systems, while the flow of hot water is heated by steam produced in fossil-fuel-fired steam boilers.

This paper will consider the use of a heat pump that will simultaneously produce ice water and hot water for the needs of the milk pasteurization process, thus eliminating the need for a fossil-fuel-fired steam boiler and ammonia (NH_3) refrigeration system.

2. METHODOLOGY

2.1. Energy and exergy analysis of milk pasteurization plant components

Milk is considered as a mixture of water, fat, carbohydrates, protein and dry residue (ash). The specific enthalpy values of various milk streams in the milk pasteurization process are determined using specific heat capacities. The expressions for determining the specific heat capacity and density of milk constituents as a function of temperature are shown in Table 1[1]. The assumed composition of raw milk is 87.8 % water, 3.6 % fat, 4.58 % Carbohydrates, 3.24 % Proteins and 0.87 % dry matter (Ash). While standardized milk consists of 88.35 % water, 3.0 % fat, 4.61 % Carbohydrates, 3.26 % Proteins and 0.87 % dry matter (Ash) [2]. The values of specific heat capacities (C_p) of various milk streams in the milk pasteurization process at characteristic points of the plant were determined using expressions (1):

$$C_p = \sum_i X_i C_{p,i} \qquad (1)$$

where Xi is the mass fraction of each constituent of the milk flow. The calculation of the exchanged heat flux (Q_{HE}) in a single heat exchanger is calculated using expression (2):

$$\dot{Q}_{HE} = \dot{m} \left(\left(\frac{C_{p_{in}} + C_{p_{out}}}{2} \right) (T_{in} - T_{out}) \right) \qquad (2)$$

where m is the mass flow rate of the flow, and T is the temperature of the fluid flow at the inlet ($_{in}$) and outlet ($_{out}$) of the heat exchanger. Within the framework of the energy analysis of the milk pasteurization plant, the heat flow values () will be determined for all heat exchangers in accordance with the law of conservation of mass and the law of conservation of energy.

Within the framework of the exergy analysis, the chemical exergy values are ignored, because in the considered process no chemical reactions occur, so the stated flow exergy values have constant values. Only the change in the physical exergy value of the fluid flow will be analyzed. The chemical exergy values are ignored in the analysis because no chemical reactions occur, so the stated value of the flow exergy has a constant value. Only the change in the physical exergy of the fluid flow will be analyzed. The physical exergy of milk and its derivatives at the characteristic points of the plant is calculated according to expression (3) [1]:

$$\dot{E}x^{ph} = \dot{m}\left[C_p\left(T - T_0 - T_0\, ln\left(\frac{T}{T_0}\right)\right) + v(P - P_0)\right] \quad (3)$$

In the framework of the exergy analysis of the milk pasteurization process, the values of resource exergy and product exergy are determined for each component of the system. Resource exergy represents the available amount of exergy that is processed in a particular component of the system, while product exergy represents the part of exergy that is realized as a product in the observed component. For each component of the system, the difference between resource exergy and product exergy represents the amount of exergy destruction in that component. In this way, it is possible to detect which component of the system has the highest value of exergy destruction.

2.2. Considered heat pump configuration and working fluids

Figure 1.b) shows the thermal scheme of the heat pump configuration with an internal heat exchanger. The internal heat exchanger allows for subcooling of the liquid phase of the working fluid and simultaneous preheating of the suction steam at the compressor inlet. The mathematical modeling of the compressor was carried out according to the methodology described in the scientific literature [3], where generalized polynomial mathematical expressions are used to model the main characteristics of a screw compressor regardless of its size and installed volumetric ratio. Ten working fluids were considered as alternative working fluids in the heat pump: Izobutan (R600a), Propan (R290), Propen (R1270), R152a, R161, R134a, R1234yf, R1225ye(Z), R1243zf and Ammonia (R717). For each working fluid, their thermodynamic, ecological and safety characteristics have been determined [4-6].

2.3. Thermodynamic parametric analysis of the use of a heat pump for heating and cooling milk flows in a milk pasteurization plant

In the considered milk pasteurization plant (gas flow diagram shown in Figure 1.a)), a flow of raw milk (3.6% fat) of 5.64 kg/s is processed, and 5.55 kg/s of pasteurized milk with a 3% fat content is obtained as a product. For the purposes of milk pasteurization, 4.395 kg/s of hot water is required, which is heated as a sink in the heat pump condenser from 71.3°C to 85°C. In the heat pump evaporator, ice water (as a source) is cooled from 6°C to 2°C. For cooling pasteurized milk, 8.31 kg/s of ice water is required.

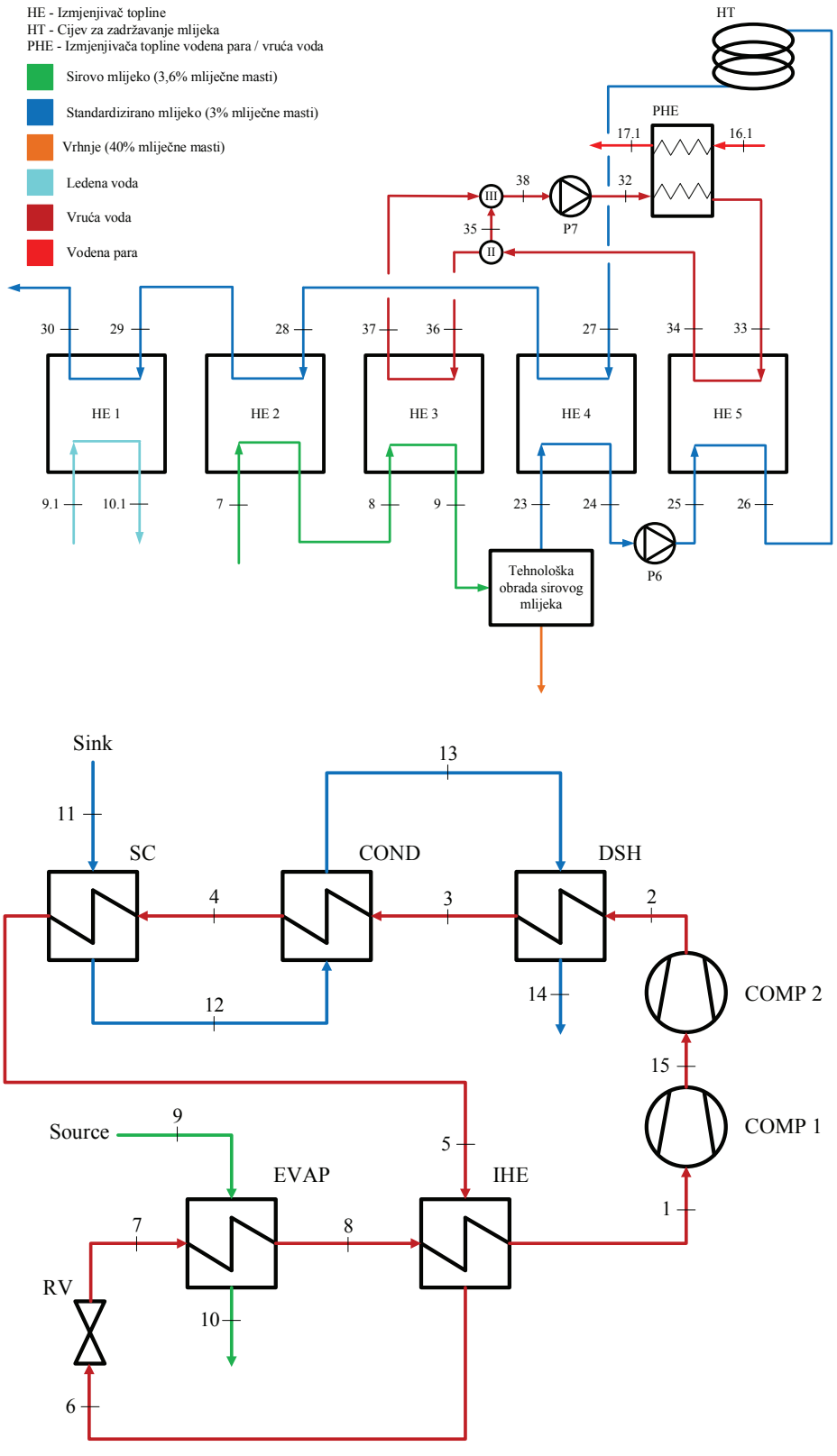


Figure 1: Thermal scheme of the (raw) milk pasteurization process (picture above), b) thermal diagram of a single-stage heat pump with internal heat exchanger configuration

Table 1: Specific heat and densities of milk constituents as a function of temperature (°C) [1]

Composition	Specific heat	Density
Water	$C_p = 4{,}1726 - \frac{9{,}0864}{10^5}T + \frac{5{,}4731}{10^6}T^2$	$\rho = 9{,}9718 \times 10^2 + \frac{3{,}1439}{10^3}T - \frac{3{,}7574}{10^3}T^2$
Fat	$C_p = 1{,}9842 + \frac{1{,}4733}{10^3}T - \frac{4{,}8008}{10^6}T^2$	$\rho = 9{,}2559 \times 10^2 - \frac{4{,}1757}{10}T$
Carbohydrates	$C_p = 1{,}5488 + \frac{1{,}9625}{10^3}T - \frac{5{,}9399}{10^6}T^2$	$\rho = 1{,}5991 \times 10^3 - \frac{3{,}1046}{10}T$
Proteins	$C_p = 2{,}0082 + \frac{1{,}2089}{10^3}T - \frac{1{,}3129}{10^6}T^2$	$\rho = 1{,}3299 \times 10^3 - \frac{5{,}184}{10}T$
Ash	$C_p = 1{,}0926 + \frac{1{,}8896}{10^3}T - \frac{3{,}6817}{10^6}T^2$	$\rho = 2{,}4238 \times 10^3 - \frac{2{,}8063}{10}T$

Thermodynamic parametric analysis of the heat pump (thermal scheme shown in Figure 1.b)) was carried out in several steps. The first step of the analysis involves optimizing the intermediate pressure at characteristic state 15, which represents the pressure between two compression stages in the operating cycle. The variant with two compressors connected in series was chosen because in the considered example we have large differences between the source and sink temperatures, which requires the realization of large values of the compression ratio, which in the design with one compressor would significantly reduce the values of the compressor efficiency. The goal of the parametric analysis is to find the value of the intermediate pressure (state 15 in Figure 1.b)) at which the highest values of the coefficient of performance for heating and cooling (COP_{HPcool}) are achieved with the lowest net compressor power (W_{comp}), as shown in Figure 2.a) for the working fluid ammonia. After finding the optimal intermediate pressure, the condensation temperature of the working fluid is determined, at which the "pinch point" value between the working fluid temperature at state 3 and the hot water temperature at state 13 (Figure 2.b)) of 5 °C is achieved.

2.4. Economic analysis of heat pump implementation

The purchase price of the heat pump represents the basic cost of purchasing individual components of the heat pump. The components of the heat pump are the heat exchangers that make up the condenser (desuperheater, condenser and subcooler), evaporator and internal heat exchanger (IHE), two compressors and a reduction valve. Component prices are determined using empirical correlations or manufacturer data [7,8]. For heat exchangers, the purchase price primarily depends on the surface [9]. The mean logarithmic temperature method was used to calculate the heat exchanger surfaces, while the coefficients of the total heat transfer in individual heat exchangers in the heat pump were selected according to recommended data from the literature [10]. The assumed type of exchanger is a warm plate heat exchanger, and the expression for determining the cost price is selected from the scientific literature [11,12].

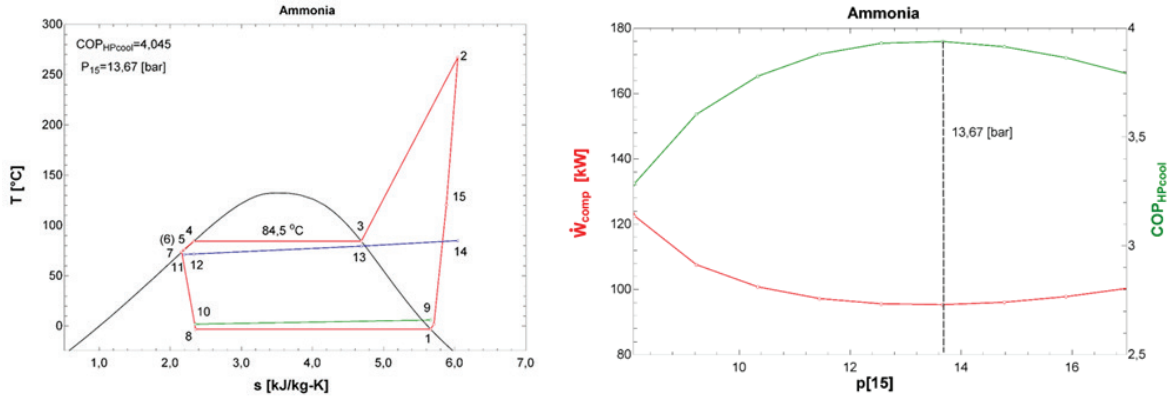


Figure 2: a) Display of the dependence of the net compressor power (W_{comp}) and the heating and cooling coefficient (COP_{HPcool}) on the intermediate pressure between the two compression stages (point 15, Figure 2) for the working fluid ammonia (left), b) display of the optimal cycle in the T - s diagram for ammonia (right)

2.5. Exergy analysis of the considered heat pump configuration

Exergy analysis of the heat pump was carried out in a similar way to the exergy analysis of the milk pasteurization process. For each component of the heat pump system, the values of resource exergy and product exergy are determined. For each component of the heat pump system, the difference between resource exergy and product exergy represents the amount of exergy destruction in that component. In this way, it is possible to detect which component of the heat pump system has the highest value of exergy destruction.

2.6. Ecological analysis of heat pump implementation in the milk pasteurization process

The ecological analysis of the milk pasteurization plant considers the implementation of a heat pump, which eliminates the existing natural gas steam generator, as well as the cooling system where ice water is produced. It is assumed that the efficiency of the natural gas steam generator is 90%, while the coefficient of performance of the existing cooling system (COP_{cool}) is ≤4. The equivalent CO_2 emission for electricity from the grid in the Republic of Croatia is 0.278 (kgCO2)/kWh), while the equivalent CO_2 emission for natural gas is 0.2286 (kgCO2)/kWh). The reduction in CO_2 emissions is determined as the difference between the total CO2 emissions of the existing system and the CO2 emissions of the new system with a heat pump.

3. ANALYSIS OF THE OBTAINED RESULTS

Figure 3.a) shows the results of the exergy analysis of the milk pasteurization plant. Based on the results shown, it can be concluded that the majority of the exergy resource and product is realized in heat exchanger 2 (HE2) and in the steam-hot water heat exchanger (PHE). The highest exergy destruction is also realized in the mentioned heat exchangers. This establishes that the mentioned components of the milk pasteurization plant are the key sources of irreversibility in the observed plant and represent the main candidates for possible optimization. Figure 3.b) shows the results of the exergy analysis of the heat pump with an internal heat exchanger, where the percentage values of exergy destruction in individual components of the heat pump for the considered working

fluids are shown. The lowest total value of exergy destruction in the system components is realized by ammonia, followed by the working fluids R152a and R161. Ammonia achieves significantly the lowest exergy destruction in the reduction valve and in both compressors, but that is why it has the highest value of exergy destruction in the desuperheater. With other working fluids, the greatest destruction of exergy occurs in the reduction valve.

The results of the thermodynamic parametric analysis of the use of a heat pump for heating and cooling milk flows in the milk pasteurization plant are shown in Figure 4. a). By analyzing the obtained results, we can conclude that the highest value of Coefficient of Performance for heating and cooling (COP_{HPcool}), for the considered heat pump with an internal heat exchanger, is achieved by ammonia as the working fluid, while the working fluids R152a and R161 achieved somewhat weaker results. The value of the total Coefficient of Performance for heating and cooling (COP_{HPcool}) for ammonia is 4,045, which represents the sum of the Coefficient of Performance for heating (COPHP) which is 2,523 and the Coefficient of Performance for cooling (COP_{cool}) which is 1,523. Figure 4.b) shows the values of total compression ratios (P_{ratio}) and total compressor power (W_{comp}) for the analyzed working fluids. It can be seen that ammonia achieves almost the highest value of compression ratio, but despite this it achieves the lowest value of total compressor power.

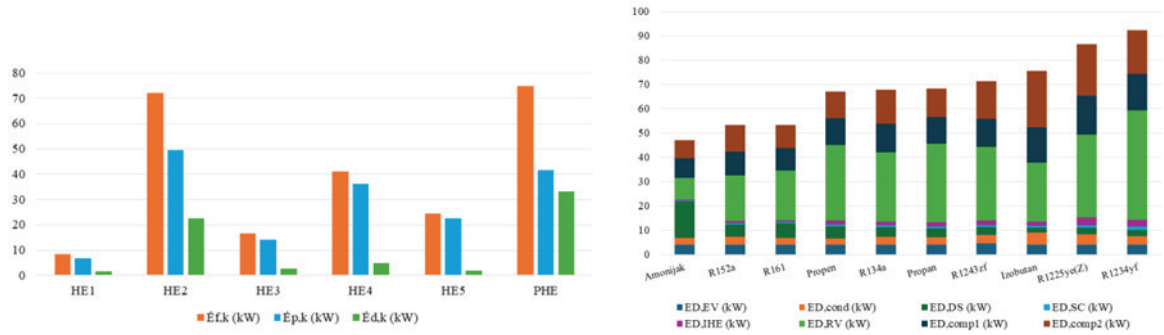


Figure 3: a) Exergy balance of the heat exchanger of a milk pasteurization plant (left), b) exergy destruction of the heat pump individual components for different working fluids (right)

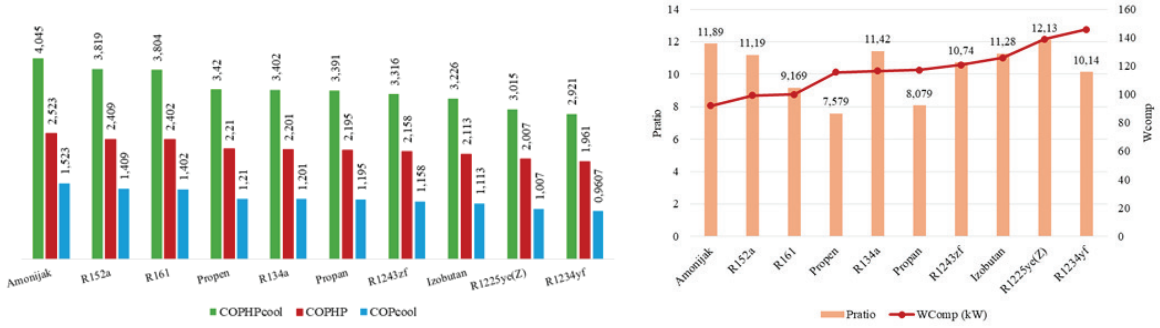


Figure 4: a) Optimal values of the Coefficient of Performance (COP) for different working fluids (left), b) overall compression ratio (P_{ratio}) and net compressor power (W_{comp})(right) for different working fluids.

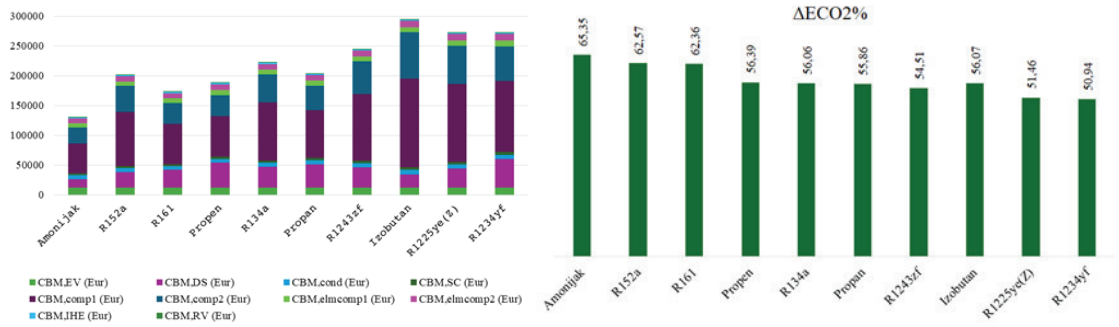


Figure 5: a) Price of heat pump components for different working fluids (left), b) CO2 emissions reduction after installation of a heat pump for different working fluids (right)

The results of the thermodynamic parametric analysis of the use of a heat pump for heating and cooling milk flows in a milk pasteurization plant are shown in Figure 4. a). By analyzing the obtained results, we can conclude that the highest value of the Coefficient of Performance for heating and cooling (COP_{HPcool}), for the considered heat pump with an internal heat exchanger, is achieved by ammonia as a working fluid, while the working fluids R152a and R161 achieved slightly weaker results. The value of the total Coefficient of Performance for heating and cooling (COP_{HPcool}) for ammonia is 4.045, which represents the sum of the Coefficient of Performance for heating (COP_{HP}) which is 2.523 and the Coefficient of Performance for cooling (COP_{cool}) which is 1.523. Figure 4.b) shows the values of the total compression ratios (P_{ratio}) and the total compressor power (W_{comp}) for the analyzed working fluids. It can be seen that ammonia achieves almost the highest value of the compression ratio, but despite this it achieves the lowest value of the total compressor power.

Figure 5.a) shows the total price of the installed equipment and the contributions of individual components of the heat pump system. The heat pump system with ammonia as the working fluid achieves the significantly lowest total cost. Compressors make up the largest share of the cost, while the cost of the desuperheater is the most significant of the heat exchangers. Other components of the heat pump system make up a small share of the total cost compared to the listed components. Figure 5.b) shows the reduction of CO_2 emissions compared to the existing system with a natural gas steam generator when using certain working fluids in the heat pump. The highest percentage of CO2 emission reduction of 65.35% is achieved by ammonia, while slightly lower values are achieved by the working fluids R161 and R152a.

4. CONCLUSION

The paper considers the possibility of implementation heat pumps in a milk pasteurization plant in such a way that the waste heat flow from the milk cooling process is used to heat the milk to 80 °C. In this way, the existing natural gas steam generator is eliminated, as well as the cooling system where ice water is produced. The analysis includes a heat pump configuration with an internal heat exchanger and ten different working fluids implementation is considered. The obtained results indicate that the implementation of heat pumps can achieve significant reductions in greenhouse gas emissions, with an acceptable economic cost of investment. Ammonia proved to be the most favorable working fluid, offering the best thermodynamic, economic and ecological performance. The value of the total Coefficient of Performance for heating and cooling (COP_{HPcool}) for ammonia

is 4.045, which represents the sum of the Coefficient of Performance for heating (COP_{HP}) which is 2.523 and the Coefficient of Performance for cooling (COP_{cool}) which is 1.523. Also, by using ammonia as a working fluid, a CO2 emission reduction of 65.35% is achieved, with the lowest heat pump installation investment costs. The conducted analysis confirms that heat pumps represent a sustainable technical and economic solution for the decarbonization of the dairy industry, contributing significantly to improved energy efficiency and reduced environmental impact. Continued research of heat pumps in the milk pasteurization process implementation should include the use of other heat pump configurations, especially two-stage designs, and the use of heat pumps exclusively for milk heating purposes.

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Original scientific paper

THERMODYNAMIC ANALYSIS OF COMBINED HEAT AND POWER ORGANIC RANKINE CYCLE CONFIGURATIONS FOR FLEXIBLE ENERGY SUPPLY

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Abstract: *Organic Rankine Cycle (ORC) systems driven by low and medium temperature heat sources can provide electricity and useful heat with low carbon emissions. This paper compares four subcritical combined heat and power (CHP) ORC configurations - split flow (SF), split flow with an internal heat exchanger (SF IHE), serial with an internal heat exchanger (Serial IHE), and parallel with an internal heat exchanger (Parallel IHE) - for a 120°C geothermal source. EES based thermodynamic optimization is used to evaluate net power output (W_{net}) and district-heating output (Q_{DH}) for multiple working fluids. SF IHE with R1234yf provides the highest net power, 1956 kW, while delivering 5640 kW of useful heat. SF IHE with propane extends the non-parallel heat output to 6718 kW at 1782 kW net power. Above approximately 6700 kW of heat demand, Parallel IHE is the only analysed configuration that can increase heat delivery, reaching 18947 kW at the cost of reducing net power to 194 kW. The resulting W_{net} - Q_{DH} boundary provides a practical configuration-selection rule for flexible geothermal CHP ORC plants.*

Keywords: *CHP ORC, configuration analysis, thermodynamic modelling, waste heat utilization, decarbonization*

1. INTRODUCTION

Organic Rankine Cycle (ORC) technology is widely applied when the available heat source temperature is too low for a conventional steam Rankine cycle but still high enough for useful power generation. Low and medium temperature geothermal resources are therefore suitable for binary ORC power plants, especially when the available geothermal heat can also be used for district heating. In such cases, the plant is not designed solely for maximum electricity production, it must also be able to deliver useful heat at the required temperature level.

Combined heat and power (CHP) ORC systems have been investigated in several layouts. The literature commonly distinguishes serial, parallel, serial/parallel and condensing arrangements.

Serial concepts generally support high heat source utilisation, while parallel concepts can provide higher supply temperatures to a thermal network. Serial/parallel concepts combine some advantages of both approaches, but also increase the number of design variables and operational constraints [1-4]. Configuration selection is therefore an important early design decision in ORC plant design, together with working fluid selection, operating pressures, pinch point temperature differences and heat exchanger arrangement.

Previous work on geothermal ORC prefeasibility studies has shown that the most suitable working fluid depends strongly on the relation between the geothermal fluid inlet temperature and the thermodynamic properties of the selected working fluid. A useful criterion is the difference between the heat source inlet temperature and the critical temperature of the working fluid. For simple subcritical ORC configurations, the highest net power output is often obtained within a certain interval of this temperature difference. However, this criterion becomes less direct when the ORC is modified for CHP operation because part of the available heat is intentionally routed to district heating [5,6]. Recent CHP studies further show that useful heat delivery, working fluid choice, and source side flow allocation should be evaluated together rather than independently [7]. Recent binary geothermal CHP research also demonstrates that geothermal source conditions, ORC operating parameters and district heating integration should be optimized jointly rather than independently [8].

The purpose of this paper is to compare four CHP ORC configurations using the same 120 °C geothermal heat source, common boundary conditions, and one optimization-result database. The comparison focuses on net power output (W_{net}) and district heating output (Q_{DH}), which directly describe the operating compromise required for flexible CHP operation. The research question is whether a clear configuration boundary can be identified: for a specified heat demand, which analysed configuration gives the highest net power, and when does a parallel arrangement become necessary?

2. METHODOLOGY

The numerical comparison includes the four configurations for which optimization results were available: split flow configuration (SF), split flow with an internal heat exchanger (SF IHE), parallel with an internal heat exchanger (Parallel IHE), and serial with an internal heat exchanger (Serial IHE). The serial/parallel concept is relevant in the literature, but it is not included in the numerically comparison because no corresponding optimization dataset was available for this study

In every configuration, geothermal fluid supplies heat to the ORC and to a district-heating exchanger. The working fluid is pumped, preheated, evaporated and, where required, superheated before turbine expansion; after expansion, it is cooled, condensed, and subcooled. When present, the internal heat exchanger transfers energy from the turbine outlet to the high-pressure liquid before external heating, reducing the geothermal heat required by the ORC and changing the heat remaining for district heating.

Figure 1 shows the analysed configurations. SF divides the geothermal flow after the ORC high temperature heating section, and SF IHE combines this principle with internal heat recovery. Parallel IHE assigns a separate geothermal branch to district heating, so Q_{DH} can be controlled through the branch mass flow. In Serial IHE, the district heating exchanger is placed in series with the ORC heat source path, which produces a fixed heat delivery level under the selected boundary conditions.

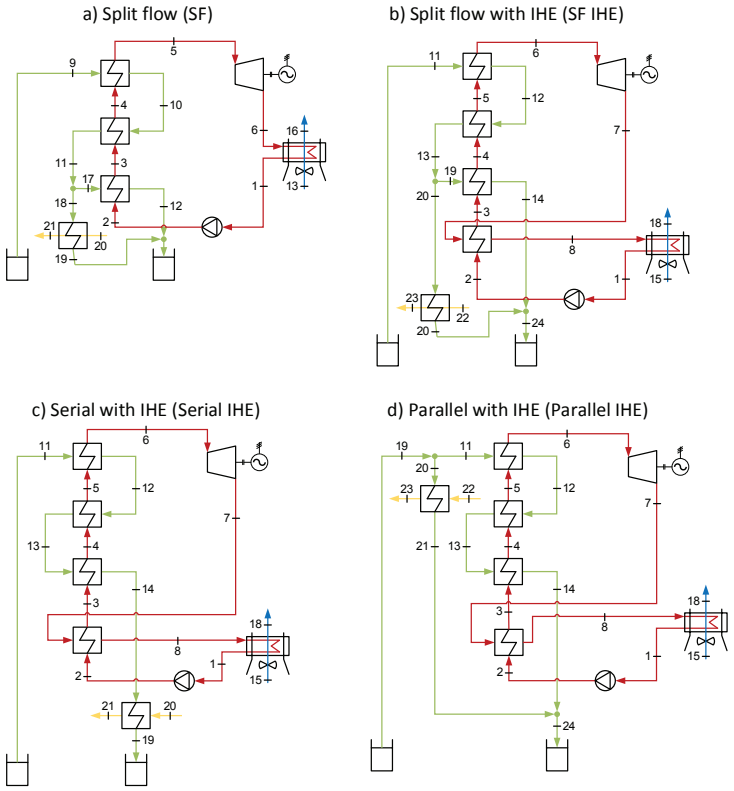


Figure 1: Analysed combined heat and power ORC configurations: split flow, split flow with IHE, serial with IHE and parallel with IHE

The thermodynamic models were developed in Engineering Equation Solver (EES). Each component was treated as a steady state control volume and described by mass conservation and first law energy balances. Heat losses and component pressure drops were neglected. Net power output (W_{net}) was calculated as turbine shaft power minus the working fluid pump input, while QDH was the heat transferred from the geothermal fluid to a district heating loop with a 60 °C return temperature and an 80 °C supply temperature.

All configurations used $T_{geo,in} = 120\,°C$, a geothermal mass flow of 100 kg/s, an ambient and cooling air inlet temperature of 20 °C, a 5 K IHE approach temperature, 2 K subcooling, turbine and pump isentropic efficiencies of 0.85 and 0.70, and mechanical efficiencies of 0.95. The geothermal fluid left the district heating exchanger at 70 °C. Maximum cycle pressure (P_{max}), pinch point temperature difference (T_{PP}), and degree of superheating (ΔT_{SH}) were optimized to maximize W_{net}. Their limits are presented in Table 1, where the maximum pressure is dependent on the critical pressure of the fluid (P_{cr}). A genetic algorithm was used with a population of 32 individuals, 200 generations and a mutation rate of 0.2625. For Parallel IHE, the optimization was repeated at fixed district heating branch mass flow ($m_{geo,DH}$) values from 0 to 90 kg/s in 10 kg/s increments; the other layouts produced one optimized point per fluid. The analysis included the same 16 working fluids considered in [5]: cyclopentane, n-pentane, isopentane, R245fa, n-butane, R236ea, isobutane, R236fa, RC318, R1234ze(E), R227ea, R134a, propane, R1234yf, propylene and R143a. Economic, environmental, and safety criteria were not included in the objective function.

Table 1: Variable optimisation limits used

Variable	Lower limit	Upper limit
P_{max}	$P_{condLTS}$	$0{,}9P_{CR}$
T_{PP}	5	30
ΔT_{SH}	5	40

3. RESULTS AND DISCUSSION

3.1. Overall comparison of net power output and district heating

The results show that configuration selection changes the feasible operating range much more strongly than working fluid selection alone. SF and SF IHE layouts provide one optimized operating point for each fluid. In Serial IHE, Q_{DH} is fixed at 6290 kW for every fluid under the selected boundary conditions. In contrast, Parallel IHE generates a family of points for each working fluid because the district heating branch flow is varied from 0 to 90 kg/s.

Figure 2 and Table 2 summarise the complete W_{net} - Q_{DH} field. The dashed line represents the non-dominated (Pareto) boundary of the analysed dataset. Points below this boundary are thermodynamically less attractive because another configuration/fluid combination produces both equal or higher power and equal or higher useful heat. The boundary begins with SF IHE using R1234yf, continues through SF IHE using propane, and then follows Parallel IHE using R1234yf as the heat demand increases. for any specified Q_{DH}, the boundary identifies the highest W_{net} among the analysed cases.

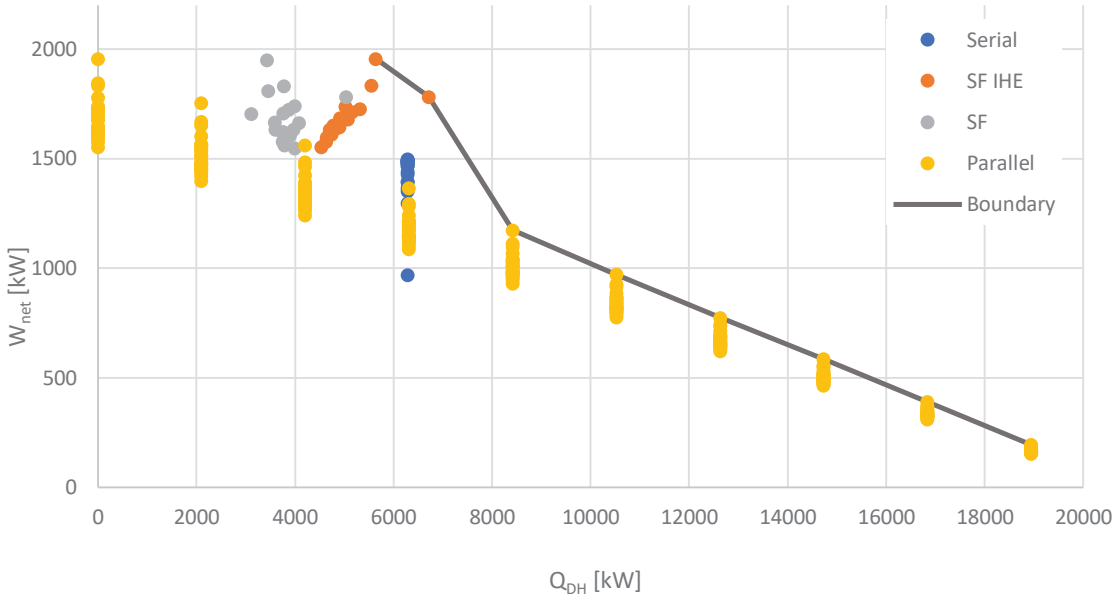


Figure 2: Net power output and district heating output for all analysed cases at $T_{geo,in} = 120\ °C$

Table 2: Representative operating points of analysed CHP ORC configurations.

Configuration	Condition	Fluid	W_{net} [kW]	Q_{DH} [kW]	Interpretation
SF	maximum W_{net}	R1234yf	1950	3440	High power, moderate heat.
SF IHE	maximum W_{net}	R1234yf	1956	5640	Best low/medium heat demand point.
SF IHE	maximum Q_{DH}	Propane	1782	6718	Upper limit of non-parallel cases.
Serial IHE	maximum W_{net}, fixed Q_{DH}	R245fa	1498	6290	Stable heat output, lower power.
Parallel IHE	high heat branch, $m_{geo,DH} = 90$ kg/s	R1234yf	194	18947	Only option for very high Q_{DH}.

3.2. Power oriented operation

When the objective is maximum W_{net}, R1234yf is the dominant working fluid in three of the four configuration families. It gives 1950 kW in SF, 1956 kW in SF IHE, and 1954 kW in Parallel IHE at a district heating branch flow of $m_{geo,DH} = 0$ kg/s. The difference between these three power values is very small, but the associated Q_{DH} is not. SF IHE is therefore superior to the basic SF: with the same fluid, useful heat increases from 3440 to 5640 kW (+2200 kW, 64%), while net power changes by only +6 kW (0.3%).

The effect of the internal heat exchanger is visible when SF and SF IHE are compared for the same fluids. For the common fluids in the dataset, the average W_{net} change is approximately +12 kW, whereas the average Q_{DH} increase is about 1005 kW. The most important practical examples are R1234yf, for which Q_{DH} increases by 2200 kW with almost no power penalty. For R227ea, useful heat increases by 2095 kW and net power rises slightly from 1810 to 1835 kW. Under the selected 120 °C conditions, the IHE therefore improves the power-heat balance primarily by increasing heat available to district heating without a meaningful power penalty.

Serial IHE does not compete with SF IHE in the power oriented region. Its best case, R245fa, produces 1498 kW at $Q_{DH} = 6290$ kW. SF IHE with propane produces 1782 kW at $Q_{DH} = 6718$ kW, corresponding to approximately 19% more net power and 7% more useful heat. Serial IHE can therefore be considered a simple fixed-heat arrangement, but it is thermodynamically dominated when the SF IHE solution is feasible.

3.3. Heat oriented operation and the operating border

The configuration boundary becomes decisive when Q_{DH} is treated as an independent design requirement. SF and SF IHE can supply useful heat while maintaining high W_{net}, but their optimized points do not extend beyond approximately 6700 kW of Q_{DH}. The serial IHE layout is close to this limit because it gives $Q_{DH} = 6290$ kW for all analysed fluids. Above approximately 6700 kW, Parallel IHE is the only analysed configuration that can continue increasing heat delivery.

The cost of this flexibility is a strong reduction in power production. For Parallel IHE with R1234yf, increasing the district heating branch flow from 0 kg/s to 90 kg/s raises Q_{DH} from 0 to 18947 kW, while W_{net} decreases from 1954 kW to 194 kW. Intermediate branch flows create a continuous trade off. At $m_{geo,DH} = 40$ kg/s, Q_{DH} is 8421 kW and W_{net} is 1173 kW. At $m_{geo,DH} = 60$ kg/s, Q_{DH} is 12632 kW and W_{net} is 775 kW. This continuous trade off enables demand matching, but it is attractive only when the required heat cannot be supplied by SF IHE.

Figure 3 presents the same results as a design oriented rule. For heat demand below approximately 5600 kW, SF IHE with R1234yf gives the highest power. Between approximately 5600 and 6700 kW, SF IHE with propane defines the non-parallel boundary. Above 6700 kW, the design must move to the Parallel IHE branch and accept the corresponding loss of net power. This is the principal configuration selection result obtained for the 120 °C source.

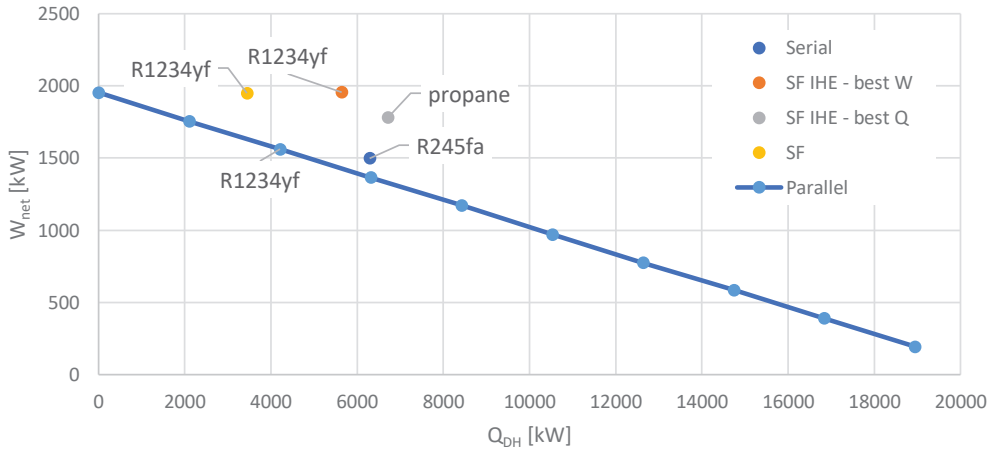


Figure 3: Configuration selection boundary between split flow/IHE solutions and the high heat Parallel IHE branch.

3.4. Working fluid tendencies

No single working fluid is best for every configuration and every operating priority. R1234yf is the most robust power producing fluid in SF, SF IHE and Parallel IHE. Propane is particularly attractive when the target is high Q_{DH} without moving to a parallel branch. R227ea also remains close to the best power results and gives a favourable balance in SF IHE. In Serial IHE, the maximum W_{net} values are reached by R245fa, R236fa, R1234ze(Z), RC318 and R236ea, which all produce between 1489 and 1498 kW because Q_{DH} is fixed and the heat source coupling dominates the operating point.

This confirms that the working fluid decision should therefore follow, rather than precede, selection of the CHP configuration and the required heat to power ratio. A fluid that is optimal for power oriented split flow operation may not be optimal for a fixed serial heat recovery configuration. Conversely, a fluid that gives a good serial result may still be dominated when a split flow IHE configuration can satisfy the same Q_{DH} requirement with higher W_{net}. Therefore, the fluid selection criterion should be applied together with the W_{net} - Q_{DH} boundary rather than as an independent ranking. Off-design and seasonal operating conditions may also affect the preferred thermodynamic and economic design; therefore, the present boundary should be regarded as a design condition screening result rather than a final plant optimum [9].

The configuration level trends agree with previous CHP ORC studies: serial arrangements favour heat source utilisation, whereas parallel arrangements provide a wider heat delivery range [1-4]. The benefit of redistributing heat source flow is also consistent with recent split-flow studies [5,6]. The present contribution is to express these trends as a quantitative W_{net} - Q_{DH} selection boundary under identical 120°C conditions. This boundary is intended for early stage screening; final selection must also consider equipment cost, part load behaviour, refrigerant safety, and environmental regulations. Propane is highly flammable, whereas some high-performing refrigerants have high global warming potential.

4. CONCLUSION

This study compared four geothermal CHP ORC configurations for a geothermal fluid inlet temperature of 120°C using W_{net} and Q_{DH} as the primary indicators. The comparison shows that the best solution depends primarily on the required heat output. SF IHE with R1234yf achieved the maximum net power in the dataset, 1956 kW, while delivering 5640 kW of useful heat. Relative to basic SF with the same fluid, the IHE increased Q_{DH} by 2200 kW (64%) while changing W_{net} by only +6 kW (0.3%).

When the heat demand increases, SF IHE with propane extends the useful heat output to 6718 kW while keeping W_{net} at 1782 kW. This point defines the upper border of the best non-parallel operating region. Serial IHE gives a similar fixed Q_{DH} level of 6290 kW, but its maximum W_{net} is only 1498 kW, so it is not thermodynamically preferable when the SF IHE solution is feasible.

Parallel IHE was the only layout that exceeded approximately 6700 kW of useful heat, reaching 18947 kW. This flexibility reduced W_{net} from 1954 to 194 kW as the district-heating branch flow increased from 0 to 90 kg/s. The practical selection rule is therefore: use SF IHE below approximately 6700 kW when net power remains important; use Parallel IHE above this threshold; and consider Serial IHE only when a simple fixed heat arrangement is preferred over maximum thermodynamic performance.

The conclusions are limited to a single geothermal inlet temperature, one set of component assumptions, and thermodynamic optimization. They should therefore be used for early stage configuration screening rather than final plant design. Future work should extend the comparison to higher source temperatures, include the serial/parallel layout, examine part load operation, and add techno economic, safety, and environmental objectives.

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Professional paper

PHASING OUT LEAD SHOT AS A MEASURE OF WETLAND AND ENVIRONMENTAL PROTECTION

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Abstract: *Lead shot is most commonly used for hunting small game, particularly wild birds, and its use contributes to environmental pollution in several areas, most notably wetlands. Therefore, this paper examines the origins and development of firearms and the extent to which their use affects the environment, as well as the legal instruments that may be used to prohibit lead shot as a measure of environmental protection. Particular attention is paid to the European Union Regulation restricting the use of lead shot and to the Ramsar Convention as legal instruments for environmental protection. The paper also addresses the harmful effects of lead on human health, as well as on plant and animal life.*

Keywords: *lead shot, wetland habitats, Ramsar Convention, environment, human health*

1. INTRODUCTION

Lead enters the environment, particularly wetland areas used for hunting, through the use of lead-based hunting ammunition, specifically lead shot. When such ammunition is discharged, the lead shot breaks down into small particles that disperse throughout the environment, thereby contributing to environmental contamination. Therefore, this paper examines the impact of lead shot on the environment, with particular emphasis on aquatic areas. This is especially important because, due to electrochemical processes, lead from lead shot can dissolve in natural waters through lead corrosion. The paper also considers the significance of phasing out lead shot through the adoption and implementation of appropriate legislation as a measure of environmental protection, with particular regard to its practicality and enforceability.

2. LEGAL FRAMEWORK

The restriction introduced by this Regulation may cause particular difficulties in some Member States due to their specific geographical conditions, especially in Member States where wetlands constitute a significant proportion of the national territory. A ban on the discharge and carrying of

lead shot in and around wetlands could, in practice, have a similar effect to a complete ban on shooting activities throughout the entire territory of a Member State, since hunters pursuing different types of game would almost inevitably frequently find themselves in or near wetlands.

Furthermore, the resources required to enforce a restriction applicable exclusively to wetlands and areas around them might not be significantly lower and could even exceed those required to enforce a restriction covering the entire national territory. In view of the difficulties described above that could arise in certain Member States, and taking into account the need for the measure to be not only effective but also simple and fair for the hunting community as a whole, the European Commission considered that Member States in which such difficulties were likely to arise should be given the possibility of introducing a different restriction.

Such a restriction would prohibit the placing on the market of lead shot, as well as the discharge and carrying of lead shot throughout the entire national territory, whether in wetlands or elsewhere, in connection with any type of shooting activity. In the interests of legal certainty, it is important to clearly identify the Member States entitled to make use of this option. The option should be available to Member States in which wetlands cover at least 20% of the national territory.

Since the restriction that such Member States could introduce would be stricter than the restriction applicable only to wetlands and areas around them, it is appropriate to provide for a longer period for the introduction of such a restriction. This period should be 36 months, i.e. three years. For reasons of transparency and legal certainty, Member States making use of this option should be required to notify the European Commission of their intention and to communicate the measures adopted for its implementation within the prescribed deadlines.

The measures provided for by this Regulation, in accordance with the opinion of the relevant Committee, appropriately amend Regulation (EC) No 1907/2006, Annex XVII, and enter into force following publication in the Official Journal of the European Union. The Regulation is binding in its entirety and directly applicable in all Member States.

Accordingly, the following provision is added to Annex XVII to Regulation (EC) No 1907/2006:

The following activities shall be prohibited after 15 February 2023 in wetlands or within 100 meters of them:

Where at least 20% of the total national territory of a Member State, excluding territorial waters, is covered by wetlands, that Member State may, from 15 February 2024, prohibit throughout its entire territory the placing on the market of shot containing lead, expressed as the metal, in a concentration equal to or greater than 1% by weight; prohibit the discharge of such shot; and prohibit the carrying of such shot while engaged in shooting or while proceeding to shoot.

For the purposes of the Regulation, “wetlands” means areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters.

Member States may retain national provisions for the protection of the environment or human health that were in force on 15 February 2021 and that restrict the use of lead in shot more strictly than provided for by the Regulation [1,2,3,4,5].

2.1. Ramsar Convention

Under the Convention, wetlands include marshes, fens, rivers, lakes, watering places, irrigated land, salt marshes, gravel pits, canals, mangroves, coral reefs, fish ponds and shrimp ponds, as well as coastal zones adjacent to wetlands and marine water bodies deeper than six metres at low tide that are located within wetland areas.

Under the Convention, wetlands are considered to be threatened by drainage, landfilling, pollution, alteration, overexploitation and the introduction of alien species [6].

The objective of the Ramsar Convention, as an international legal instrument, is to conserve those areas of the Earth that are of crucial importance for the survival of numerous plant and animal species and their communities, many of which are used by humans and upon which humans depend to some extent. This objective is pursued through recognition of the multiple beneficial functions that wetlands perform for human society [7].

The Ramsar Convention entered into force in 1975, when its depositary institution, UNESCO, received the instruments of ratification from the first seven countries. Membership in the Convention is open to countries that are members of the United Nations. The Convention also cooperates closely with numerous international non-governmental organizations, including IUCN, WWF and Wetlands International, as well as with other international entities that participate as partners or observers.

Today, the Ramsar Convention has 168 Contracting Parties and is one of the oldest international instruments addressing nature conservation. Upon accession to the Convention, each country must designate, according to established criteria, at least one wetland area that it undertakes to conserve and maintain in the long term. Such areas are included in the List of Wetlands of International Importance, commonly known as the Ramsar List. To date, the Ramsar List includes 2,177 sites covering a total area of approximately 209 million hectares across all continents [6].

At Croatia's request, full membership was recognized on 25 June 1991, when the decision on separation from the other parts of the former state was adopted. In 1993, the Republic of Croatia nominated four of its wetlands for inclusion on the Ramsar List:

Lonjsko Polje Nature Park is the largest floodplain and retention area in the Sava River valley. The various ecological conditions that change spatially and throughout the year support the development of diverse biological communities. The area of the Nature Park is also characterised by special values associated with traditional livestock farming practices and traditional rural architecture.

Kopački Rit Nature Park represents an inland delta and floodplain at the confluence of the Drava and Danube rivers. Its rich biodiversity has been recognised for centuries, while it has enjoyed legal protection since 1967. The area is also important from a vegetation perspective due to its well-developed floodplain forests. Its importance for birdlife is reflected in the presence of numerous rare species, including the black stork, white-tailed eagle and lesser spotted eagle, which regularly inhabit the Nature Park. The abundance of water during flooding also makes the area an important fish spawning ground in this part of the Danube basin.

The Neretva River Delta is the only true delta in Croatia and has retained, to a considerable extent, its characteristic wetland and marshland features. It belongs to the rare relict Mediterranean wetlands with preserved coastal lagoons.

The delta is particularly important from an ornithological perspective. A total of 310 resident, migratory and wintering bird species have been recorded there. The area is also important from an ichthyological perspective and is unique for its traditional method of land cultivation known as jazenje. The area's cultural heritage is also rich due to thousands of years of human settlement.

Crna Mlaka fishponds, located near Jastrebarsko, represent the smallest of these areas. Nevertheless, particularly during winter, the site provides an opportunity to observe the richness of birdlife that either migrates to the area or resides there permanently. The area is protected as an ornithological reserve.

On 2 February 2013, a fifth Croatian wetland of international importance was added to the Ramsar List: Vransko Lake Nature Park.

Vransko Lake is the largest natural, brackish, permanent body of water in Croatia and is of exceptional importance for numerous endangered and rare bird species in Europe. During at least one part of their life cycle, approximately 60% of Croatia's total bird fauna has been recorded at Vransko Lake, including as many as 136 species threatened at the global, European or national level. For certain bird species, such as the squacco heron and little cormorant, the area represents the only remaining breeding site in Croatia [6].

2.2. Mediterranean Wetlands Initiative (MedWet)

The Mediterranean Wetlands Initiative (MedWet) was established in 1991 in support of the Ramsar Convention, bringing together 27 Mediterranean and peri-Mediterranean countries that are Contracting Parties to the Convention. It operates under the motto “Wetlands for a Sustainable Mediterranean Region.”

MedWet is a regional intergovernmental network operating within the framework of the Ramsar Convention and involving other key stakeholders. It is dedicated to promoting and supporting policies and field-level actions aimed at the conservation, restoration and sustainable use of Mediterranean wetlands.

As an organisation, MedWet creates synergies with a broad range of intergovernmental and non-governmental partners, encouraging and supporting them in adopting policies and implementing actions that benefit the conservation and sustainable use of Mediterranean wetlands.

Accordingly, the organisation's vision is to ensure that the resources and functions of Mediterranean wetlands are conserved in the long term and restored where necessary for the benefit of both nature and people. Its mission is to ensure and support the effective conservation of the functions and values of Mediterranean wetlands, as well as the sustainable use of their resources and services [8].

2.3. Natura 2000

Natura 2000 comprises more than 27,000 natural sites protected under European Union legislation across the territories of EU Member States. Natura 2000 sites maintain Europe's rich diversity of wild species and habitats and cover almost one-fifth of the continent's land area and approximately one-tenth of its surrounding seas.

The Natura 2000 network is based on the Birds Directive and the Habitats Directive (the “Nature Directives”), which have provided the general legal framework for the protection of Natura 2000 sites for more than 30 years.

Natura 2000 sites range in size from less than one hectare to several hundred square kilometres. They include a number of strictly protected natural reserves and habitat types, such as forests, grasslands, wetlands, and coastal and marine habitats.

The Natura 2000 ecological network in the Republic of Croatia covers 25,956 km², representing 36.8% of the country's land territory and 9.3% of the marine area under national jurisdiction, including the territorial sea and the exclusive economic zone of the Republic of Croatia.

2.4. Hunting Act (Official Gazette No. 99/18)

According to Article 4 of the Hunting Act, the objective of its implementation is to ensure the sustainable management of game populations and their habitats in a manner and to an extent that permanently improves the vitality of game populations, the productive capacity of habitats and biological diversity, thereby ensuring the fulfilment of economic, tourism and recreational functions, as well as the protection and conservation of biological diversity and the ecological balance of natural habitats, game species, and wild flora and fauna [11].

According to Article 44 of the Act, a hunting management plan is a planning document that regulates in detail the management, breeding, protection, hunting and use of specific game species and hunting grounds for a period of ten hunting years, in accordance with habitat capacity and the abundance and condition of game populations managed in open and enclosed hunting grounds.

Such a planning document is based on the population numbers of all game species that permanently or seasonally inhabit the hunting ground and on the number of game animals that can be maintained within the hunting ground, while taking into account the presence of strictly protected animal species that affect or are affected by hunting management, without disturbing natural relationships between species.

Furthermore, the population size and structure of the game being bred or that may be bred within a hunting ground must be achieved within the period established by the hunting management plan. This period may not exceed five years for small game and ten years for large game.

Article 48 stipulates that hunting management plans must be consistent with forest management plans, the conditions and methods of agricultural land use, spatial plans and specific regulations governing spatial planning and environmental and nature protection. They must also comply with international agreements to which the Republic of Croatia is a party in the fields of hunting and nature conservation, as well as with European Union legislation governing the conservation of wild species and natural habitats [11,12].

3. CONCLUSION

Lead is a metal that has been used for centuries. However, with each passing day and with the publication of new research by various organisations concerned with environmental protection and human health, the extent of its toxicity is becoming increasingly evident, affecting virtually all components of the environment.

It is therefore highly justified to regard the prohibition of lead shot as an important component of environmental protection, particularly the protection of water resources. Lead discharged into

wetland habitats remains on the ground and is therefore accessible to animals; at the same time, it can dissolve through lead corrosion in natural waters and subsequently enter soil and plants.

The strategy for phasing out lead shot has been well conceived and strategically developed through European Union legislation. However, it is rather disappointing that the laws and regulations governing hunting in the Republic of Croatia do not clearly address this issue and, moreover, do not explicitly refer to the relevant EU Regulation.

These circumstances appear particularly contradictory given that the Republic of Croatia is a Contracting Party to the Ramsar Convention and participates in MedWet and the Natura 2000 ecological network. Therefore, the Republic of Croatia should make considerably greater efforts to ensure the practical implementation of the relevant EU Regulation so that it does not remain merely "a dead letter on paper" but becomes a fully effective component of environmental protection.

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Professional paper

WASTE MANAGMENT IN A HELATHCARE INSTITUTION

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Abstract: *Medical waste is generated in the provision of health care and can be hazardous and non-hazardous waste. Healthcare institutions are the largest producers of hazardous medical waste. With the growth of the healthcare industry, the production of medical waste has increased sharply, and thus there is an increased need for proper management of medical waste due to the potential dangers it poses to human health and the environment in which we live. The aim of the paper is to investigate the medical waste management system in the Republic of Croatia and the effectiveness of its application in reducing the amount and volume of waste in healthcare institutions. The research on the amount of collected medical waste was conducted in the period from 2019 to 2024. The analysis of the results obtained showed that the smallest amounts of hazardous medical waste were obtained during 2019 and 2021, and the largest in 2023 and 2024. For non-hazardous medical waste, the largest amounts were obtained in 2019 and 2024, and the smallest amounts were obtained in 2022 and 2023.*

Keywords: *medical waste, environmental risks, health risks, medical waste disposal*

1. INTRODUCTION

Waste can be defined as a discarded substance or object that requires collection, transportation, and treatment to maintain environmental cleanliness. Nowadays, significant attention is paid to waste because irresponsible handling or disposal can lead to environmental pollution. Medical waste is a by-product of healthcare activities in hospitals, health research centres, and medical laboratories. As the healthcare industry expands and healthcare services improve, the generation of medical waste is also increasing rapidly. Medical waste contains potentially infectious and hazardous substances. Managing waste in an environmentally friendly manner is essential for protecting the public interest.

Requirements for medical waste management in healthcare facilities are defined by legal regulations and internationally recognized accreditation standards for healthcare organizations (e.g., AACI – American Accreditation Commission International). The growing volume of medical

waste generated at the Croatian Institute of Public Health (HZJZ) resulting from an increase in the number of healthcare services and procedures is raising concerns regarding environmental and public health risks. Of the total waste generated by healthcare activities, approximately 85% is non-hazardous waste. The remaining 15% is classified as hazardous waste, typically comprising infectious waste and chemical waste. Measures ensuring safe and environmentally sound medical waste management can prevent the adverse effects such waste may have on health and the environment. Under Croatian regulations, the medical waste generator is required to collect medical waste separately, place it in appropriate containers, and store it temporarily in a designated area until it is processed or handed over to an authorized entity holding the prescribed permit for medical waste management; records of these activities must also be maintained. Furthermore, the entity authorized to collect and transport medical waste must have a contract in place for the handover of collected waste to an entity authorized to process, recover, and/or dispose of medical waste. A portion of infectious medical waste is treated in specialized units using sterilization or autoclaving processes, after which it is handled as non-hazardous waste. Although Croatian regulations define all steps in the waste management chain, certain irregularities arise during their implementation.

The aim of this paper is to present the types and quantities of medical waste generated at the Croatian Institute of Public Health over a period of six years.

2. MEDICAL WASTE: PROPERTIES AND TYPES

Any waste that has substances with the following properties: infectiousness, toxicity, carcinogenicity, mutagenicity and ecotoxicity is considered hazardous medical waste. Medical waste is materials generated in institutions such as hospitals, health centres, laboratories, homes for the elderly, dental, veterinary and other practices. Treatment of medical waste is prescribed by the institution's internal regulations, according to which employees should act (Figure 1).

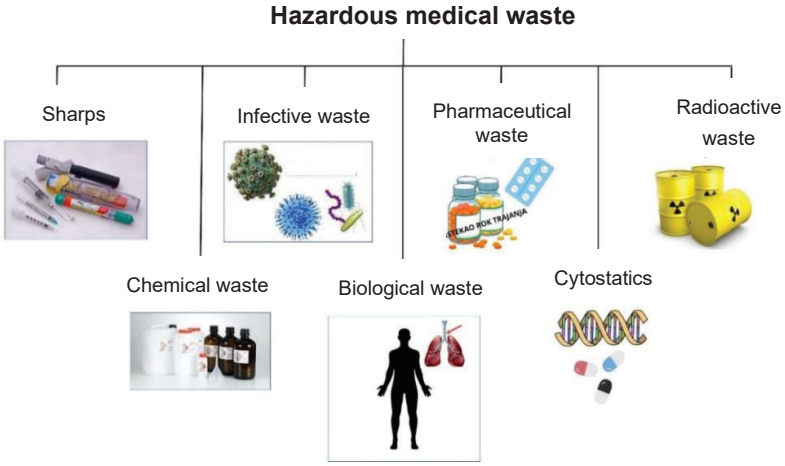


Figure 1. Medical waste

Healthcare facility staff are at risk primarily from punctures caused by sharp objects that have not been safely packaged as are individuals who scavenge through waste in dumpsters and at landfills. The unsafe and improper storage of medical waste poses a serious threat to public health.

2.1. Legal regulations for medical waste

Legal regulations serve as the starting point for all waste, establishing guidelines for its management (Figure 2). Laws and regulations provide common guidelines aimed at protecting human health and the environment, requiring waste to be separated and collected according to type. Such practices encourage the recycling and reuse of waste, thereby reducing the volume of medical waste ultimately sent for disposal.



Figure 2. Fundamental legal regulations

3. RESULTS

Table 1 presents an overview of all reported quantities of medical waste generated, categorized by type (waste codes), for the period from 2019 to 2024. Quantities for each specific type of medical waste generated at the HZJZ in Croatia were calculated for the 2019–2024 period. Graphs were plotted and percentages of the total quantity were determined for each combination of hazardous medical waste types over the 2019–2024 period. The following types of hazardous medical waste were analyzed: EWC 18 01 03* infectious waste; EWC 15 01 10* packaging; EWC 16 05 06* laboratory chemicals; EWC 06 04 04* mercury containing waste; EWC 15 02 02* absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, and protective clothing contaminated by hazardous substances; EWC 20 01 33* batteries; EWC 14 06 03* other solvents and solvent mixtures; EWC 18 01 06* chemicals.

Table 1. Quantities of hazardous medical waste at the HZJZ in the period from 2019 to 2024.

	18 01 03*	15 01 10*	16 05 06*	15 02 02*	20 01 33*	14 06 03*	18 01 06*	Total
2019.	1153,50	313,00	1711,00	0	0	0	0	3177,50
2020.	3169,50	262,50	979,00	99,00	0	0	0	4510,00
2021.	1815,50	399,00	559,00	79,00	47,00	0	0	2899,50
2022.	3610,90	252,00	1143,00	55,00	52,00	75,00	0	5187,90
2023.	13 831,00	108,00	792,00	107,00	0	0	263,00	15 101,00
2024.	13 201,00	139,00	188,00	131,00	106,00	0	1092,00	14 857,00

18 01 03* wastes whose collection and disposal is subject to special requirements in order to prevent infection
15 01 10* packaging containing residues of or contaminated by hazardous substances
16 05 06* laboratory chemicals, consisting of or containing hazardous substances, including mixtures of laboratory chemicals
15 02 02* absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, protective clothing contaminated by hazardous substances
20 01 33* batteries and accumulators included in 16 06 01, 16 06 02 or 16 06 03 and unsorted batteries and accumulators containing these batteries
14 06 03* other solvents and solvent mixtures
18 01 06* chemicals consisting of or containing hazardous substances

Table 2 presents the quantities of non-hazardous medical waste at the HZJZ for the period from 2019 to 2024. For each year, the quantities of specific types of non-hazardous medical waste at the HZJZ were calculated. Total quantities were calculated, charts were drawn, and percentages were determined for each year. The following types of non-hazardous medical waste were analysed: EWC 18 01 04 autoclaved waste, EWC 18 01 09 medicines, EWC 08 03 18 used toner cartridges, EWC 20 01 25 edible oils and fats, EWC 15 01 07 glass packaging, EWC 18 01 01 sharps, EWC 20 01 34 batteries, and EWC 15 02 03 absorbents and filter materials.

Table 2. Quantities of non-hazardous medical waste in the period from 2019 to 2024.

	1801 04	180109	08 03 18	20 01 25	15 01 07	18 01 01	20 01 34	15 02 03	Total
2019.	6.721,50	340,00	231,00	52,00	0	55,00	0	0	7.399,50
2020.	7.511,40	612,00	257,00	0	54,00	153,00	0	0	8.589,40
2021.	6.639,50	586,00	0	0	0	231,50	0	0	7.457,00
2022.	7.953,00	690,00	0	0	538,00	175,00	0	0	9.356,00
2023.	49,00	10.429,00	0	0	446,00	0	50,00	816,00	11.790.00
2024.	0	5.494,50	0	0	480,00	51,00	0	0	6.025,50

18 01 04 wastes whose collection and disposal is not subject to special requirements in order to prevent infection (for example dressings, plaster casts, linen, disposable clothing, diapers)
18 01 09 medicines other than those mentioned in 18 01 08
08 03 18 toners
20 01 25 edible oil and fat
15 01 07 glass packaging
18 01 01 sharps (except 18 01 03)
20 01 34 batteries and accumulators other than those mentioned in 20 01 33
15 02 03 absorbents, filter materials, wiping cloths and protective clothing other than those mentioned in 15 02 02

The graph (Figure 3) shows that the quantities of medical waste (hazardous and non-hazardous) generated at the HZJZ between 2019 and 2024 amounted to 45,733 kg of hazardous medical waste and 50,618 kg of non-hazardous medical waste.

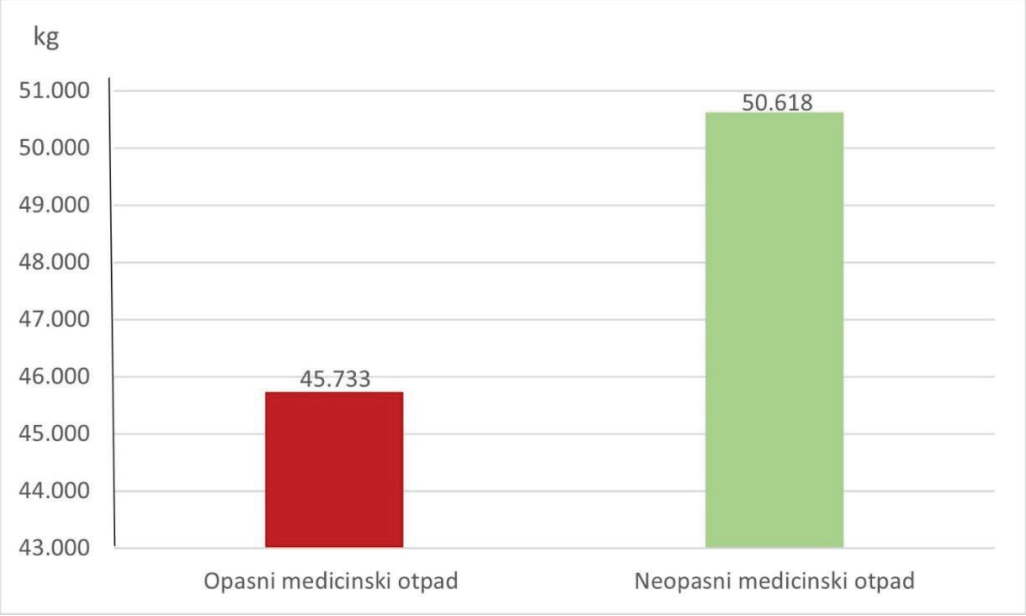


Figure 3. Total amount of medical waste generated at the HZJZ from 2019 to 2024.

4. CONCLUSION

Medical waste contains infectious and harmful substances that can have serious health impacts. Waste released onto the soil or into surface water or groundwater poses an environment risk. This paper proposes five key long-term opportunities for developing sustainable and resilient waste management systems: managing medical waste appropriately by treating it as a critical area of focus; fostering the integration and decentralization of waste management facilities; developing systematic, novel approaches and tools for waste classification; transitioning to a circular economy model; and modernizing policies to improve the efficiency of waste management infrastructure. Regarding the first research question (concerning the types of medical waste disposed of by the HZJZ between 2019 and 2024), an analysis of disposal volumes reveals that the highest quantities of medical waste were recorded in 2019 and 2021. Furthermore, the lowest volumes of hazardous medical waste were generated in 2019 and 2021, and the highest in 2023 and 2024. Volumes of non-hazardous medical waste were lowest in 2019 and 2024, and highest in 2022 and 2023. Regarding the second research question concerning the causes of the increase in certain types of medical waste at the HZJZ between 2019 and 2024, it can be concluded that the increase observed from 2019 to 2021 is linked to the COVID-19 pandemic. The further increase during the 2022–2024 period is associated with building renovations following the earthquake. The largest quantities of non-hazardous medical waste were generated during 2022 and 2023. Regarding the third research question, about establishing a safe and efficient information system and ensuring oversight of the system in accordance with current regulations, it can be said that creating an information system and ensuring oversight of the system in line with current regulations is necessary. It's important to think about the issue of collecting hazardous medical waste in public health and to provide insights into policies and recommendations as well as experiences from other countries, which can be applied both locally and nationally. Regarding the first hypothesis, that HZJZ handled primarily medical waste categorized as infectious waste from 2019 to 2024, the smallest amounts of total medical waste were generated in 2019 and 2021.The largest amounts of total medical waste were generated during 2023 and 2024. Based on the analysis carried out, the first hypothesis was confirmed because it was proven that there were larger amounts of medical waste from 2019 to 2024. Regarding the second hypothesis, that there was a significant increase in the total amount of medical waste handled by HZJZ in the period from 2019 to 2024, the analysis showed an increase in the amount of hazardous medical waste produced from 2019 to 2024. Based on the analysis carried out, the hypothesis is confirmed. The work is expected to contribute to a better understanding of the dynamics of collection, transport, processing, and disposal of medical waste at HZJZ, which can be a useful basis for improving the system for planning future waste disposal recommendations and for raising employees' awareness of the importance of proper collection and sorting of medical waste. The quantities and types of medical waste at the Croatian Institute of Public Health depend on the quantity and type of work tasks.

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Original scientific paper

CHALLENGES OF SUSTAINABLE WASTE MANAGEMENT: AN INTERDISCIPLINARY APPROACH TO SOCIAL ASPECTS OF ZAGREB'S TRANSITION

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Abstract: *The European Green Deal often fails to answer contemporary environmental issues. In Croatia, the implementation of environmental solutions leads to civil resistance, indicating insufficient integration of community members. The focus is on the challenges of waste management, where the crisis at Jakuševec Landfill and resistance to the Waste Management Centre in Resnik are symptomatic of a disparity between professional policies and public opinion. In contrast, the Recycled Estate in Vukomerić showcases a successful example of inclusive participation and high social cohesion. The methodological framework integrates natural parameters with qualitative methods to provide a framework for an inclusive model of sustainability. Consequently, cooperation between social and environmental sciences is key to bridging the gap between policies and their implementation, and environmental goals and the needs of local communities in addressing current environmental challenges.*

Keywords: *civic engagement, interdisciplinary approach, waste management, Zagreb*

1. INTRODUCTION

In practice, the European Union, through its policy focused on environmental protection and the requirements of the European Green Deal (EGD) [1, 2], faces numerous challenges. Environmental protection and the green transition present a complex domain and are regulated by a vast number of laws and regulations, as they encompass different sub-domains, among which waste management is one [3]. These challenges are the result of insufficient consideration of the socio-economic context and sole reliance on the techno-administrative approach. In Croatia, such inconsistency is clearly manifested through the long-standing waste management crisis, especially in the City of Zagreb (CoZg) – most visible in the examples of the Jakuševec landfill [4], and the increasingly pronounced public resistance to the planned construction of the Waste Management Centre (WMC) in Resnik [5].

The lack of civic engagement in decision-making processes results in the population's greater distrust and stronger opposition. This points to a clear need for a transformation of the current governance model – it is essential to design a system that respects the perspectives of local communities and encourages closer collaboration between natural sciences and social sciences to find a compromise between theoretical green models and proper community solutions [6, 7]. Anthropological approaches to waste are particularly relevant here, as the discipline has long treated waste not merely as an environmental by-product, but as a culturally constituted category. What is considered a "matter out of place" mirrors underlying social classifications and boundaries [8]. Such an approach frames public resistance to waste facilities as an expression of deeper symbolic and social concerns about pollution, contamination, and community boundaries. Public resistance is most commonly described through the NIMBY effect. However, sociological analyses show that citizens' reactions are not unfounded but rather a direct response to the lack of transparency and poor communication [9, 10]. When decision-makers rely exclusively on expert and technical assessments, they completely ignore local perceptions, fears and interests over the distribution of the environment, which leads to violations of the principles of ecological justice [11, 12]. From a (culturo)anthropological standpoint, such conflicts can also be understood through the prism of political ecology, which examines how environmental decision-making is shaped by power relations between institutions, experts, and local communities [13]. In contrast to such an approach, the paper also presents the results of an analysis of the Vukomerić Recycled Estate's (ZMAG) model [14] as an example of good practice of sustainability at the local level. In ZMAG's case, high social cohesion and horizontal participation successfully generate ecological responsibility within the community [15].

Based on the theoretical foundations mentioned above, the paper is focused on three key research hypotheses:

H1: Citizens who believe they are directly affected by environmental problems are more likely to engage in civic resistance and protests against such projects.

H2: The perception of EU and Croatian environmental policies as ineffective correlates with the way they are communicated to the public.

H3: There is a strong connection between citizens recognising successful examples of environmental sustainability initiated by civil society organizations (e.g., Vukomerić) and their greater willingness to participate in such projects. Thus, the horizontal models achieve a higher degree of inclusiveness.

The study uses a mixed-methods approach that integrates quantitative and qualitative methods. By linking the gathered empirical data with socio-ecological parameters of sustainability, this study aims to map the green transition dynamics within CoZg. The results are intended to serve as a framework for designing a new, more inclusive approach to sustainability, where citizens are key co-creators of environmental solutions in urban areas.

2. METHODOLOGY

The study combines a mixed-methods design – a quantitative online survey with a qualitative semi-structured interview, thus allowing the integration of public attitudes with an in-depth perspective from practitioners of the aforementioned good-practice case. An anonymous online survey was conducted between April and June 2026, consisting of 19 questions with an initial section gathering

demographic and educational background information and a substantive section addressing the paper's core themes through 12 closed-type and 7 Likert-scale questions. The survey was distributed via snowball sampling on social media and was filled out by 136 voluntary respondents from all Croatian counties. As reported in Section 4, the sample's demographic distribution (gender, age, education) mostly corresponds to national parameters [16], which supports its use as an indicative public opinion; it should not, however, be treated as statistically representative in the probability sense. However, to complement the survey with practice-based insight, the authors conducted a semi-structured interview with a representative of the ZMAG. The interviewee was selected to gain an inside perspective. The interview was conducted online and was coded around social cohesion, trust, and models of participation. Quantitative data were processed using descriptive statistics, while qualitative interview data were analysed thematically and used to contextualise the interpretation of the survey findings, especially regarding the mechanisms behind ZMAG's successful social cohesion. This approach emphasises practitioners' personal frameworks and lived experience [17].

3. LEGISLATIVE FRAMEWORK

An integrated legislative framework is essential for effective environmental protection, particularly waste management. Consequently, the EU has regulated this field with relevant legal acts, regulations, and directives aimed at environmental protection through waste management and the achievement of a circular economy. The waste management system in the Republic of Croatia is legally based on EU legislation, which has been fully transposed into the national Waste Management Act [18]. The Waste Framework Directive [18, 19] is vital to establishing the waste management hierarchy and stipulates that at least 55% of municipal waste must be recycled by 2025 (which did not happen). The Landfill Directive [20], on the other hand, obliges Member States to reduce the amount of waste sent to landfills to a maximum of 10% by 2035. In order to meet the above-mentioned environmental standards and avoid severe penalties, complementary regulations (e.g., the Packaging Waste Directive and the Industrial Emissions Directive [18]) are used, as they ensure that the waste treatment facilities have a minimal impact on the environment. The CoZg thus plans to build a WMC, which represents a step towards the final closure of the Jakuševec landfill and harmonisation with the EU's ecological standards. According to the official waste management plan, a modern facility is envisioned. It will integrate the mechanical-biological treatment (MBT) of mixed municipal waste with the sorting of separately collected plastic, paper, and cardboard, as well as a biogas plant for bio-waste treatment with compost production. Fig. 1 showcases the plan.

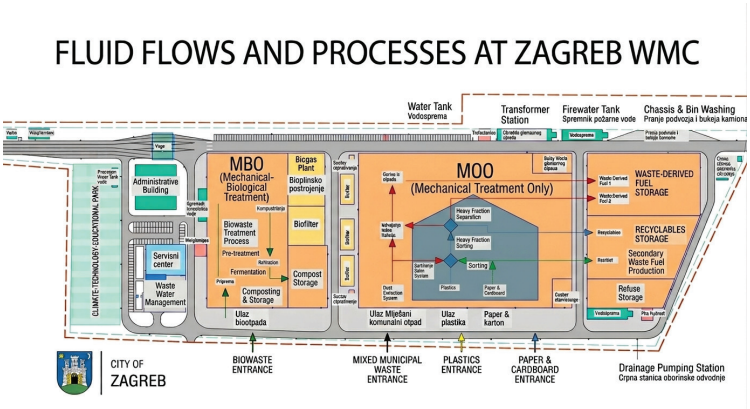


Figure 1. Planned processes at WMC Zagreb (adapted from the source: https://media.jutarnji.hr/images/slike/2026/01/11/o_36492366_1280.jpg)

The City announced the construction of the WMC facility, envisioned as an alternative to the Jakuševec landfill, which has posed a challenge for years to citizens and other actors involved in waste management processes. The planned centre's purpose is not the disposal of waste; rather, through the application of state-of-the-art technologies, it is designed to process collected mixed municipal waste, dry recyclable components, and bio-waste. The goal is to use sorting plants, a composting facility, and mechanical-biological treatment to extract components that can be reused or recycled, thereby minimising the remaining inert portion of the waste in accordance with the previously presented EU eco-standards.

4. RESULTS AND DISCUSSION

Qualitative results of the survey conducted among Croatian citizens show that the general population is dissatisfied with the legislation, its implementation, and civic involvement in waste management issues. Among the 136 voluntary participants, 49.6% (67) were female, and 50.4% (68) were male. The majority (47.1%) are from Zagreb and Zagreb County (16.9%), while 36% are dispersed through the remaining 19 counties. 8.8% of participants are in the 18-25 age group, 16.9% are in the 26-35 age group, and 41.9% are in the 36-45 age group. The remaining are aged 46-65+. 44.1% of participants hold a bachelor's degree, whilst 22.8% have a high school degree, and 29.8% a master's degree. 3.7% obtained a PhD. Virtually all the statistics correlate with the national statistical parameters of Croatian society [16]. Thus, although the number of participants is relatively small, the data show that the sample is representative in describing the opinions of Croatian citizens. Nonetheless, 84.6% of participants are not employed in the environmental protection sector, and the remaining 15.4% work in some form of environmental protection. This inevitably shows that the majority of the participants are actors of the civil society, whose environmental and ecological concerns are solely private matters.

The authors then investigated (1) whether the informants feel directly affected by the local ecological problems, such as the vicinity of the waste disposal, and poor air quality; (2) whether they are familiar with the goals of the EGD; (3) to what extent they think the EU and national ecological politics deal effectively with the ecological problems in their surroundings; and finally (4) how would they rate the communication between the institutions (e.g. the city government, ministries, and the state) with the citizens when new ecological solutions are being implemented.

Informants gave an average rating of 3.35 (out of 5) when asked about the direct effect of the ecological issues. 2.61 was the average score of how well they are informed about the EGD goals. A slightly lower rating (2.37) was given to the EU and national efficiency in solving local ecological problems, which suggests a high distrust of the authorities. However, distrust is also indicative of the fact that communication between the authorities and civil society was given the lowest rating (2.08).

The respondents were then asked which problems related to the crisis at Jakuševec landfill and the Waste Management Centre in Resnik they would emphasise as symptomatic. The consensus is that the majority of participants are concerned about their health and the possible deterioration of their living conditions. Poor technological and professional solutions, and decision-making without the participation/consent of the local community followed. Whether they support civil resistance in such cases was further questioned, with 3.57 agreeing.

As almost complete distrust in national, supra-national, and local institutions is evident from the previous answers, the authors wanted to know which factors would encourage participants to join

the environmental project (e.g., a waste management facility, composting plant or sorting plant) in their micro-communities. Full transparency and independent control, i.e. concrete evidence that the plant will not pollute the air, soil or water, with constant public data monitoring was cited most commonly, accompanied by "None of the above: I do not want such a facility near a residential area, regardless of the conditions", involving the citizens in managing such issues, as well as the possibility of economic benefits for the household (for example, reducing utility bills).

Examples of good practices, such as the Green Network of Activist Groups (ZMAG), show that civic involvement in the decision-making and implementation of city and national regulations can be successful. However, only a portion of the participants have heard about ZMAG (31.6%).

Community can be perceived as a symbolically constructed entity bounded by shared meaning, mutual recognition, and a sense of belonging [21] (which ZMAG recognises as demanding and long-lasting); participants had to rate level(s) of connectedness and solidarity in their communities. The low connectedness reported by the wider survey sample (Fig. 2) suggests that community cohesion of this kind should be cultivated through sustained relational work, which may explain why horizontally organised, community-initiated efforts outperform top-down interventions.

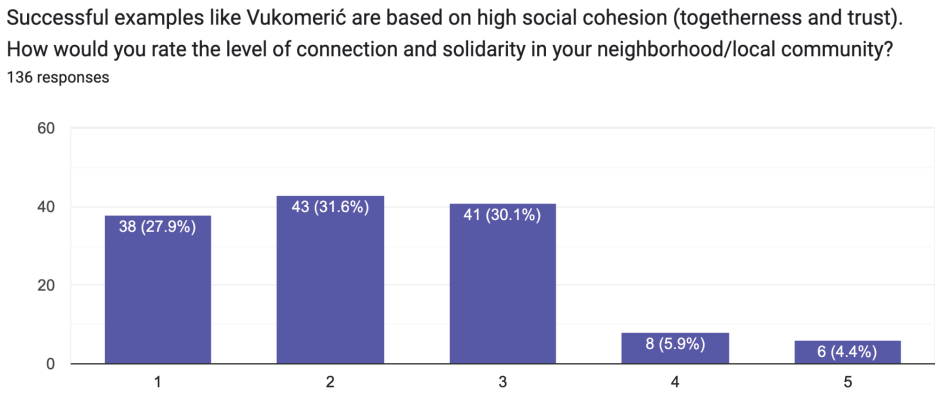


Fig. 2. The perceived degree of connectedness and solidarity in local communities (source: authors' survey).

Nonetheless, when asked whether they would actively participate in sustainability projects (e.g. community gardens, local composting, renewable energy cooperatives) if they were initiated by the community, 3.48 answered positively.

The participants were to rank the overlooked components in the implementation of new ecological policies. "Lost trust – citizens do not trust the institutions that the promised projects will be carried out according to regulations and without corruption" was voted as the leading problem, followed by the infrastructural unpreparedness, inadequacy and unadaptedness to the local context ("policies are copied from the EU without understanding how people really live and think"); and a fear of new, unregularised financial costs that the average family will not be able to finance.

What is more, almost 60% think natural scientists and environmental experts should be the authorities in decision-making of ecological projects; the interplay of natural and social scientists, civil society (organizations), and politicians was ranked second. ZMAG opted for the same answer.

Finally, the authors investigated how environmental protection goals can best be aligned with the citizens' needs. 35.3% of participants voted that it will be done successfully through education and long-term training – it ought to be done from a young age and through constant, clear campaigns explaining why such practices are important. ZMAG's head of organization also emphasized the importance of education in such matters – sustainable living should be nurtured, developed, and encouraged. 33.1% stated it is best done through strict and fair control, while ensuring top-notch infrastructure is a prerequisite to severely punishing those (both institutions and individuals) who do not follow the rules. 19.9% believe it could be achieved through financial incentives and rewards, as the state or city should subsidize and financially facilitate citizens' environmental decisions. Finally, models of shared decision-making, local referendums and public forums held before every major project, 11.8% of participants claim to be most effective.

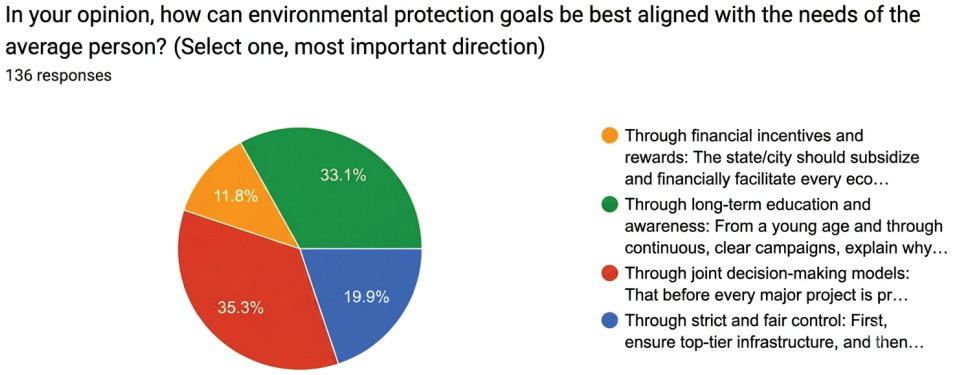


Fig. 3. Pie chart on how environmental protection goals can best be aligned with the needs of common people (source: authors' survey).

5. CONCLUSION

The survey findings point to a high level of public distrust towards local, national, and supranational institutions regarding waste management. While the sample of 136 respondents was not randomly selected and cannot be considered fully representative, its demographic profile aligns closely with national statistical indicators, suggesting the findings may be indicative of wider public sentiment; they should be interpreted with caution. The results are consistent with H1 – respondents reported that local environmental problems affect them directly (3.35/5), particularly through concerns about health and quality of life, thus significantly supporting civic resistance and public protest (3.57/5). Regarding H2, participants rated the effectiveness of EU and national environmental policies relatively low (2.37/5), while communication between institutions and citizens received the lowest score in the survey (2.08/5). These two parameters are consistent with the link between perceived policy ineffectiveness and poor communication. However, this should be interpreted as suggestive evidence; the authors recommend it as a direction for follow-up analysis. H3 received only partial support. Namely, awareness of ZMAG – a model of successful horizontal governance – remained limited (31.6%), yet willingness to participate in community-initiated sustainability projects was considerable (3.48/5). The gap suggests the hypothesis cannot be considered fully confirmed based on these data alone. Participants identified three priority areas for improving the alignment between environmental policy and public needs: education and long-term awareness campaigns

(35.3%), stricter and fairer regulatory oversight (33.1%), and greater transparency paired with technical expertise. A majority favoured a leading role for interdisciplinary scientists in decision-making, along with public access to information, and direct community involvement. The limitations of this study include its sample, which was demographically broad and recruited voluntarily, and introduces self-selection bias toward individuals already engaged with environmental issues. The qualitative component was limited to a single interview with a ZMAG representative, which cannot be generalised to other civil-society initiatives. Future research would benefit from probability-based sampling and a broader interview base spanning multiple civic organisations. Overall, the findings suggest that institutions engaged in environmentally significant projects would benefit from more participatory approaches which would rebuild public trust, improve communication, and ensure that local communities, civil society, and experts are included in decision-making processes.

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Review article

SUSTAINABILITY AND FOOD WASTE REDUCTION IN PROFESSIONAL KITCHENS

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Abstract: *This paper examines the critical issue of food waste in professional kitchens, focusing on the intersection of environmental sustainability, operational efficiency, and food safety. The hospitality and foodservice sector contributes to global food wastage, representing a substantial portion of national waste streams in many developed economies. By analysing both scientific evidence and professional practice, the study explores modern mitigation strategies, including the integration of Green HACCP principles and digital food waste monitoring systems. The interview findings suggest that standardized operating procedures, staff training, menu engineering, and digital monitoring can contribute to reducing avoidable food waste and improving operational efficiency. The study highlights that integrating sustainability into daily operations through process standardization and targeted employee training is vital for reducing the environmental carbon footprint and enhancing the long-term financial viability of catering operations.*

Keywords: *food waste, professional kitchens, sustainability, Green HACCP, hospitality management.*

1. INTRODUCTION

Food waste has emerged as one of the most pressing environmental and economic challenges for the hospitality and foodservice sector. Recent data highlights the alarming scale of this issue: in the United Kingdom, the HaFS (Hospitality and Food Service industry) sector generates 1.1 million tonns of food waste annually, representing 12% of the total food wasted across the nation's supply chain [1]. In the United States, the sector's impact is even more substantial, accounting for approximately 40% of the nation's total annual food waste, which amounts to 25 million tonnes [1].

Professional kitchens, characterized by high production volumes and fluctuating guest demands, are particularly vulnerable to inefficiencies. In addition to its environmental impact, food waste increases procurement and disposal costs and may create public-health challenges when waste

is inadequately managed [2]. Foodborne diseases continue to pose significant threats worldwide, often exacerbated by shortcomings in waste management, personal hygiene, and temperature regulation in catering establishments [3]. The integration of "Green HACCP" protocols provides a framework for addressing these issues simultaneously. Green HACCP extends the traditional focus on consumer protection by incorporating environmental concerns such as excessive water and energy consumption [4]. This paper analyzes how digital optimization, standard processes, and specialized training can mitigate waste and improve overall resource efficiency.

2. DYNAMICS OF FOOD WASTE IN CATERING OPERATIONS

The generation of food waste varies significantly across different service models and institutional settings. Understanding these dynamics is essential for identifying where the greatest reductions can be achieved.

2.1. Hotel and Buffet Waste Patterns

Research conducted in 4- and 5-star hotels shows that the highest amount of food waste typically occurs during evening open buffet meals [5]. This is largely due to the operational requirement to maintain visual abundance for guests until the end of the service period. Among the most common areas of waste, bread products have been identified as the most frequently discarded category in these environments [5].

2.2. Institutional and Healthcare Service

The healthcare foodservice sector also faces substantial challenges regarding waste and its associated carbon footprint. A comparative assessment conducted across hospital settings found that food waste at lunch ranges between 8.6% and 13.9%, while dinner waste is often higher, ranging from 7.0% to 18.4% [5]. The environmental cost of this waste is high, with the carbon footprint for lunch estimated at 6.9–11.5 kgCO_2eq per week per person, and 6.4–7.0 kg CO_2 eq for dinner [7]. Strategies to minimize this waste include improving the food delivery system, enhancing meal presentation, and implementing "room service" models to better align with patient preferences [6].

2.3. AI and Digital Waste Tracking

Modern technological interventions are proving highly effective in reducing avoidable losses. AI-based food waste analysis systems, such as KITRO, have been implemented in the HORECA (Hotel, Restaurant and Café) sector with measurable success [7]. At baseline, total food waste in these settings was recorded at 76–152 g/meal [7]. The use of AI tracking devices resulted in a 23–51% reduction in total food waste and reduced the cost of wasted food per meal by up to 39% [7]. These devices not only provide data but also serve to raise significant staff awareness about the scale of wastage [8].

3. CAUSES AND ENABLERS OF FOOD WASTE

Food waste in the catering industry is driven by a complex interplay of operational, behavioral, and logistical factors. At the procurement stage, inaccurate forecasting and a lack of real-time inventory management often lead to over-purchasing, creating a surplus that is difficult to manage within shelf-life constraints [9].

During preparation, waste may result from non-standardized recipes, varying staff skills, inefficient trimming, and limited reuse of by-products. Furthermore, over-production remains a systemic challenge, particularly in buffet-style service where the aesthetic of abundance is prioritized over actual consumption volumes [9].

Finally, plate waste constitutes a major portion of the total waste stream, often resulting from rigid portion sizes and non-functional garnishes that do not align with guest preferences. Addressing these enablers requires a shift from traditional experience-based workflows to integrated management systems that combine technical training with enhanced operational oversight [10].

4. SUSTAINABILITY THROUGH GREEN HACCP

Green HACCP can be considered an extension of the traditional HACCP system, as digital tools improve traceability, compliance readiness, and sustainability while also reducing water and energy consumption in professional food production [11].

Green HACCP extends traditional food-safety management by addressing environmental issues such as chemical discharge, energy inefficiency, and water waste [4]. Evidence from industry applications, including the bakery and seafood sectors, shows the following measurable benefits:

Water Consumption: Reductions of 20–25% through optimized cleaning protocols and digital monitoring [4]. Energy Efficiency: Savings of 10–15% through predictive optimization and IoT-based monitoring of equipment [3]. Compliance and Safety: Improved compliance readiness through real-time traceability and digital technologies like blockchain and AI [4]. By aligning safety protocols with the United Nations Sustainable Development Goals, Green HACCP provides a cost-effective and scalable model for the future of professional food production [4].

5. STRATEGIES FOR WASTE MINIMIZATION

Effective waste reduction in professional kitchens requires a dual approach that combines technical interventions with a shift in organizational culture. On the operational side, the integration of data-driven analytics has become a cornerstone of modern kitchen management. Historical consumption data and real-time tracking can improve procurement forecasts, inventory levels, and alignment between purchasing and actual demand [9].

Technological advancements, particularly AI-based waste analysis systems, provide the necessary visibility into specific loss points. These tools allow for targeted corrections in both preparation techniques and portioning strategies, transforming raw data into actionable insights for the culinary team [7].

Beyond technical solutions, the human element is vital for long-lasting results. Leadership from senior chefs is essential for establishing a culture of resource respect, where junior staff are mentored in efficient preparation skills and waste mitigation. Visual feedback from monitoring devices serves as a powerful educational tool, raising collective awareness about the financial and environmental costs of discarded food. Furthermore, strategic adjustments to service models such as the implementation of flexible menu designs and "room-service" style delivery can significantly reduce plate waste by aligning production more closely with guest expectations and preferences [12].

6. METHODOLOGY

The methodology of this paper is based on a qualitative case study approach, examing food waste management within professional kitchens. A central component of this research is the author's professional background in the hospitality industry, which provides an "insider" perspective. This practical experience allows for a more nuanced analysis of operational challenges and kitchen dynamics that may not be fully captured by external observation alone.

Data collection was conducted through participant observation during high-intensity service periods and semi-structured interviews with two experienced hospitality professionals. Respondent A was an Executive Chef aged over 50 with more than 30 years of professional experience in hotels, independent restaurants, and private catering operations. Respondent B was a Food & Beverage Manager aged over 50 with more than 25 years of professional experience in hotel operations and hospitality management. The interviews lasted approximately one hour and followed a predefined interview guide covering procurement planning, inventory management, food preparation, food waste reduction strategies, staff training, digital food waste monitoring, and sustainable kitchen operations. By synthesizing theoretical frameworks with practical industry insights, the study aims to provide actionable conclusions for improving sustainability in catering operations.

7. CASE STUDY AND DISCUSSION

By examining procurement, preparation, and service stages, the study demonstrated that a substantial proportion of waste can be prevented through improved process management.

Storage-related losses and inconsistent FIFO (First In, First Out) implementation, accounting for approximately 10% of total waste in this study, are consistent with findings reported by Khoddami [13], where inventory management, procurement planning, and storage control were identified as major determinants of food waste generation in the hospitality sector. Similarly, Stanciu et al., 2024 [14] state that proper stock rotation and optimized procurement are among the key preventive measures for reducing food waste across the food supply chain.

During food preparation, this study showed that insufficient technical competency may result in raw material losses of up to 18%, while the implementation of Standard Operating Procedures reduced preparation waste by an average of 12%. This is consistent with Khoddami (2026) [13], who emphasizes standardization, training, and preparation control.

The largest proportion of waste identified in this study originated from plate waste associated with oversized portions and decorative garnishes, representing approximately 30% of total discarded food. These results confirm conclusions reported by Stanciu et al., (2024) [14], where portion size, menu design, and consumer behavior are recognized among the primary drivers of food waste in food-service environments.

The evaluated mitigation strategies demonstrated considerable effectiveness in reducing food waste within professional kitchen operations. Menu engineering, ingredient cross-utilization, and digital waste tracking contributed to improved resource management, reduced surplus generation, and enhanced operational efficiency.

8. CONCLUSION

This study shows that food waste in professional kitchens is a complex operational problem with environmental and economic consequences. The main sources of avoidable waste identified in the study were inadequate inventory control, inconsistent stock rotation, inefficient food preparation, overproduction, oversized portions, and plate waste.

The findings indicate that standard operating procedures, consistent application of the FIFO principle, employee training, menu engineering, ingredient cross-utilization, and digital waste monitoring can contribute to reducing food waste and improving operational efficiency. These measures are particularly effective when supported by managerial supervision and a workplace culture that encourages responsible use of food and other resources.

The empirical findings are based on interviews with only two experienced hospitality professionals and therefore cannot be statistically generalised. Nevertheless, they provide valuable practical insights into the prevention of food waste in professional kitchen operations. Further research involving a larger number of establishments, more participants, and direct measurement of food waste would be useful for evaluating the effectiveness of individual reduction strategies.

Reducing food waste requires a proactive management approach in which waste is treated as a measurable and preventable loss. Combining standardized procedures, employee education, effective inventory management, and digital monitoring can help catering operations improve resource efficiency, reduce their environmental impact, and support long-term sustainability.

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Original scientific paper

CAMPSITES MANAGERS' ENVIRONMENTAL PRACTICES AND ENVIRONMENTALLY RESPONSIBLE BEHAVIOUR IN CROATIA

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Abstract: *The paper aims to analyze the relationship between tourism experience (TE), managers' practices in campsites (MP), managers' environmental knowledge (MEK), and their environmentally responsible behaviour in campsites (ERB) in Croatia. A survey on TE, MP, MEK, and ERB among managers was conducted across 15 campsites in Croatia and analyzed using IBM SPSS Statistics Version 31. The research showed a high level of environmental awareness among campsite managers. As an example of good practice for environmental protection in campsites, the use of electric scooters is highlighted as an effective measure to reduce carbon emissions and promote sustainable mobility within camping facilities.*

Keywords: *tourism experience, managers' environmental practices, environmental knowledge, environmentally responsible behaviour, campsites, electric scooters*

1. INTRODUCTION

Camping tourism is a part of the tourism industry defined as a recreational activity in natural settings [1]. This paper investigates attitudes of the managers in campsites and their environmentally responsible behaviour. In the paper, the relationship between tourism experience (TE), managers' practices in campsites (MP), managers' environmental knowledge (EK), and their environmentally responsible behaviour in campsites (ERB) in Croatia is researched. Specific goals have been set: (1) present a literature review of construct TE, MP, MEK, and their ERB, (2) determine the relationship between the basic constructs.

In addition, three main hypotheses were developed.

H1: There is a positive and significant relationship between tourism experience and managers' practices in campsites.

H2: There is a positive and significant relationship between managers' practices in campsites and environmentally responsible behaviour.

H3: There is a positive and significant relationship between managers' practices in campsites and managers' environmental knowledge.

H4: There is a positive and significant relationship between managers' environmental knowledge and environmentally responsible behaviour.

The managerial aim is manifested in determining which constructs contribute to the ERB the most. Tourism managers will be able to plan marketing strategies and design tourism products and services that will contribute to the TE and ERB of managers in campsites, and how to prevent further devastation of the environment in campsites.

The paper consists of six chapters. The introductory part, explaining the purpose, the goals and the hypothesis of the research, is followed by a description of the basic concepts in the theoretical framework, a description of the methodology and the results of the empirical research. The paper ends with the discussion part and the conclusion.

2. LITERATURE REVIEW

2.1. Tourism experience (TE)

Tourism experience is a set of emotional, psychological and intellectual state of consciousness of a tourist in interaction with a specific place [2]. Hosany and Witham (2010) describe TE as overall impressions from a trip [3]. The camping experience is particularly transformative, enhancing connections to nature and social interactions [4]. Research on TE began in the 1960s but gained traction in the 1990s with Pine and Gilmore's "Experience Economy" [2]. Since then, numerous studies have researched tourism experience [2], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. Pine and Gilmore (1998) identified four dimensions of tourism experience: aesthetics, entertainment, education, and escapism [2]. Schmitt (1999) added five dimensions: emotional, sensory, thinking, operational, and relational [16]. Although a definitive scale for TE is still being developed, many researchers have built a scale based on Pine and Gilmore's framework. This paper analyses the four dimensions of TE in camping tourism.

2.2. Managers' practices in campsites (MP)

Preziosi et al. (2019) interviewed five green hotel managers to gain insights into their environmental practices [17]. Their findings confirm that implementing green practices in hotels increases market awareness and guest loyalty. Kim et al. (2017) describe green practices as a value-added business strategy that supports environmental protection and benefits hospitality operations [18]. These community-driven actions enhance financial and commercial value while minimizing environmental impact [18]. In campsites, managers achieve resource efficiency and reduce water and energy consumption through such practices [13]. Positive experiences in campsites can encourage tourists

to seek similar environmentally responsible options in the future [13]. Preziosi et al. (2019) further note that environmental certification enhances the hotel guest experience [17].

2.3. Managers' environmental knowledge (MEK)

Managers' environmental knowledge refers to the understanding and awareness that managers possess regarding environmental issues, sustainability practices, environmental regulations, and the environmental consequences of organizational activities. According to Cialdini et al. (1990), environmental knowledge is an important antecedent of pro-environmental decision-making [19], while studies by Hoffman (2000) emphasize that managerial understanding of environmental challenges influences strategic responses to sustainability issues [20]. Furthermore, research by Hart (1995) suggests that managers with strong environmental knowledge are better positioned to identify opportunities for green innovation and sustainable competitive advantage [21]. Consequently, environmental knowledge is widely recognized as a key driver of environmental commitment, sustainable business practices, and improved organizational environmental performance. Regarding MEK Arredondo et al. (2021) find five variables that managers can act upon: campsite type, offsite slope, tree canopy cover, distance to other sites, and rugosity [22]. Knowledge of ecologically sustainable sites is only effective if managers can successfully direct visitors to these locations. Incorporating visitor campsite preferences into the development of a campsite inventory is necessary to address socially defined preferences. Managerial sustainability encompasses considerations such as financial resources, staffing, and maintenance capabilities, including the removal of large hazardous trees [22].

One of the practices that campsite managers have started to introduce in recent years is the use of electric scooters as an internal means of transport. Campsites often cover large areas, so guests and staff need to move between receptions, pitches, beaches and other facilities several times a day. When these short trips are made by electric scooters instead of cars, local emissions of CO2 are avoided and noise within the campsite is reduced, which also contributes to the quality of guests' stay. Research shows that electric scooters can replace a considerable share of short car trips and thereby reduce greenhouse gas emissions [23], [24]. In the context of campsites, electric scooters can therefore be seen as a practical example of sustainable mobility that connects managers' environmental practices with the environmentally responsible behaviour promoted among guests.

2.4. Environmentally responsible behaviour (ERB)

The tourism industry significantly pollutes the environment due to its growth-focused development [25]. It leads to higher CO2 emissions, increased resource consumption, more waste, and coastal damage. Climate change concerns are growing [25]. Tourist activities often harm ecosystems [26], causing pollution, overcrowding, and disturbances to wildlife, damage to vegetation, the spread of plant seeds, and the collection of flora and fauna [28]. ERB is defined as action by individuals or groups who are concerned about the natural environment and about ways to address environmental problems [29]. It refers to advocacy for sustainable, reduced use of natural resources, and to actions intended to promote environmental sustainability and minimise negative impacts [30]. Lee et al. (2013) developed a scale for measuring both general and site-specific environmentally responsible behaviour [31]. Site-specific environmentally responsible behaviour comprises three dimensions: pro-environmental behaviour, sustainable behaviour, and environmentally friendly behaviour. In camping tourism, the site-specific environmentally responsible behaviour scale by Cegur Radović et al. (2022) identifies five dimensions: encouraging others to behave responsibly, sustainable behaviour on a campsite, responsible behaviour towards flora and fauna, responsible use of products, and responsible behaviour on a campsite [32].

3. RESEARCH METHODOLOGY

3.1. Measurement Scale

The questionnaire consists of 14 statements on TE [3], 14 statements on MP [17], 4 statements on MEK [17] and 14 statements on ERB [32]. All statements were measured using a seven-point Likert scale.

3.2. Data collection and sample

The survey was conducted on a convenience sample of managers at campsites. Managers completed questionnaires addressing TE, MP, MEK, and ERB. The research was conducted online in Google Forms from May to October 2024. The questionnaires were sent to 29 campsite managers in Croatia and a total of 15 questionnaires were collected and included in the further analysis (51.7%). IBM SPSS Statistics (version 31) was used to perform data analysis, and descriptive statistics were used, while Cronbach's alpha was used to evaluate internal consistency.

4. FINDINGS

An online survey examining the relationship between four constructs: TE, MP, MEK, and ERB, defined as actions taken to minimize environmental impact, was conducted with 15 campsite managers in Croatia. For TE, mean scores ranged from 5.93 to 6.87, the mode is 7, and most standard deviations were below 1, for campsite management practices, mean scores ranged from 2.20 to 6.60, the mode between 1 and 7, and most standard deviations exceeding 1, indicating dispersion. Overall, responses were positively oriented, with the exception of the statement *"The campsite grows its own food for its guests,"* as most campsites do not provide their own food (79.9%). MEK showed high consistency (100%), with mean scores ranging from 6.33 to 6.93, a mode of 7, and standard deviations below 1. This suggests that campsite managers possess consistently high levels of environmental knowledge. Regarding ERB, mean knowledge scores ranged from 4.53 to 6.87, mode is between 6 and 7 and standard deviation indicates dispersion. All responses in this category were positively oriented.

Spearman's correlation coefficient measures the relationship between constructs. A weak correlation ranges from 0 to +0.39, a positive medium correlation from +0.4 to +0.59, a positive strong correlation from +0.6 to +0.79, and a very strong positive correlation is from 0.80 to +1 [33]. The correlation analysis revealed no significant correlation between tourism experience and management practices ($r = 0.324$, $p<0.238$). The correlation analysis revealed a statistically significant and strong positive correlation between campsite management practices and environmentally responsible behaviour of managers ($r = 0.781$, $p<0.001$). There was no significant correlation between management practices in campsites and environmental knowledge ($r = 0.176$, $p<0.530$), nor between environmental knowledge and environmentally responsible behaviour of managers in campsites ($r = 0.469$, $p<0.078$), indicating that these relationships were not supported by the data. Cronbach's Alpha ranges from 0.638 to 0.870. The comparatively lower Cronbach's alpha is for MP (0.638).

Table 1. Constructs, variables, mean, mode, standard deviation

TOURISM EXPERIENCE	MEAN	MODE	ST DEV	Cronbach's Alpha
1. The setting of the campsite was attractive.	6.87	7	0.352	0.870
2. The setting of the campsite pays close attention to design details.	6.80	7	0.414	
3. I felt comfortable staying in the campsite.	6.67	7	0.724	
4. I felt a real sense of harmony.	6.87	7	0.352	
5. The campsite activities were interesting.	6.60	7	0.352	
6. The campsite activities were amazing.	6.20	7	0.632	
7. The campsite activities were entertaining.	6.53	7	0.862	
8. The experience in the campsite made me more knowledgeable.	6.33	7	0.743	
9. It was a real learning experience.	6.13	7	0.816	
10. It stimulated my curiosity to learn new things.	6.13	7	1.407	
11. I felt I played a different character here.	5.93	7	0.990	
12. The experience let me imagine being somewhere else.	6.60	7	1.223	
13. I completely escaped from my daily routine.	6.33	7	0.632	
14. I felt I was in a different time or place.	6.87	7	1.234	
MANAGERS' PRACTICES IN CAMPSITES	**MEAN**	**MODE**	**ST DEV**	**Cronbach's Alpha**
1. Electricity saving techniques are implemented at the campsite.	5.93	7	1.580	0.638
2. Water saving techniques are implemented at the campsite.	5.67	7	1.234	
3. The campsite has noise control system.	4.07	6	1.944	
4. The campsite uses thermostats to control the temperature in mobile homes.	4.00	7	2.726	
5. The campsite uses energy efficient lightening.	6.27	7	1.387	
6. The campsite offers its guests to use towels more than once if they are staying more than one night.	6.60	7	0.737	
7. The campsite uses rechargeable appliances.	5.53	7	2.031	
8. The campsite participates in various programmes for environmental protection organized by the local community.	6.33	7	1.175	
9. The campsite buys food from local producers.	5.33	7	1.988	
10. The campsite grows its own food for their guests.	2.20	1	1.740	
11. The campsite uses products with eco-labels.	4.73	7	2.017	
12. The campsite provides education for its employees on environmental protection.	5.20	7	2.016	
13. The campsite has policies regarding environmental/ sustainable reporting.	5.73	7	1.821	
14. The campsite promotes environmental protection to its guests.	6.40	7	0.986	
MANAGERS ENVIRONMENTAL KNOWLEDGE	**MEAN**	**MODE**	**ST DEV**	**Cronbach's Alpha**
1. Maintaining the ecological balance will improve the sustainable development of the campsite.	6.6	7	0.632	0.732
2. We must protect the natural resources in the campsite surrounding for future generations.	6.87	7	0.352	
3. Maintaining biodiversity in the campsite surroundings is very important.	6.93	7	0.259	
4. The development of mass tourism depletes natural resources.	6.33	7	0.900	

ENVIRONMENTALLY RESPONSIBLE BEHAVIOUR OF MANAGERS IN CAMPSITES	MEAN	MODE	ST DEV	Cronbach's Alpha
1. At the campsite, there are clearly marked places for guests' recreational activities (hiking, jogging, cycling).	6.27	7	0.884	0.833
2. At the campsite, there are warning signs about not harming plants and animals.	4.53	7	2.475	
3. Environmentally friendly products are used at the campsite	5.8	7	1.082	
4. At the campsite, there are warning signs against making noise.	5.2	6	2.007	
5. There is a waste separation area in the campsite.	6.8	7	0.775	
6. At the campsite, special care is taken to maintain cleanliness.	6.87	7	0.358	
7. At the campsite, guests are suggested to minimise the use of cars as a means of transport.	5.13	7	1.922	
8. The campsite has specially marked places for throwing cigarette butts and chewing gums.	5.4	7	2.063	
9. The campsite encourages guests to save water during their stay.	6.27	7	1.010	
10. The campsite encourages guests to save energy during their stay.	6.27	7	0.961	
11. The campsite encourages guests not to disturb the animals or damage the plants in the campsite surroundings.	6.13	7	1.356	
12. The campsite encourages guests to separate waste.	6.67	7	0.816	
13. The campsite encourages guests to pick up the waste they left behind.	6.00	7	1.6476	
14. The campsite encourages guests to leave the place as clean as it was before their arrival.	6.53	7	0.834	

Source: research results

It can be concluded that management in campsites can have an impact on the environmentally responsible behaviour of tourists conducting environmentally responsible practices in campsites. Managers in campsites have highly environmentally responsible behaviour, which they try to educate tourists about.

5. DISCUSSION AND CONCLUSION

This paper explores how TE shapes MP in campsites and how these practices influence MEK and ERB in Croatian campsites. The findings contribute to both theory and practice by clarifying the impact of MP on ERB. Results indicate that campsite managers in Croatia possess a high level of MEK, and correlation analysis shows a statistically significant, strong positive relationship between MP and ERB ($r = 0.781$, $p<0.001$). There are no significant relationships between TE and MP in campsites, nor between management practices in campsites and environmental knowledge ($r = 0.176$, $p<0.530$), and between MEK and ERB of managers in campsites ($r = 0.469$, $p<0.078$) there are no significant relationships. Hypothesis H2 was confirmed, but hypothesis H1, H3 and H4 weren't confirmed.

From a managerial point of view, the results also point to areas where MP can still be improved. The statement suggests that guests should minimise the use of cars to receive one of the lower mean scores in the environmentally responsible behaviour scale (5.13), which indicates that mobility within campsites has not yet been fully addressed. Introducing electric scooters for guests and staff is one measure that managers can apply relatively easily. It reduces carbon emissions and noise, supports

sustainable mobility within the campsite, and at the same time sends guests a clear message about the environmental orientation of the campsite. In this way, electric scooters can be highlighted as an example of good practice that links managers' environmental practices with their ERB.

This study is limited by its use of convenience sampling and its focus on Croatian campsites. Future research should include cross-cultural comparisons to assess how social norms, cultural values, and environmental attitudes influence the relationship between MP and ERB. Longitudinal studies are also recommended to monitor behavioural changes over time and evaluate the persistence of sustainable practices after campsite visits. Additionally, incorporating psychological constructs such as place attachment, environmental identity, and social influence may enhance the explanatory power of models predicting pro-environmental behaviour.

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Original scientific paper

BACTERIOPHAGE T4-FUNCTIONALIZED 3D-PRINTED MEMBRANES FOR REDUCING *ESCHERICHIA COLI* SURFACE COLONIZATION: A PILOT STUDY

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Abstract: *The PhageGuard project is an interdisciplinary pilot study in which bacteriophage T4 was passively adsorbed onto 3D-printed PETG membranes to reduce bacterial colonization and biofilm formation on membrane surfaces. Phage-treated and untreated membranes were compared in batch culture with gentle agitation (50 rpm) and no flow-through, in three biological repetitions, each with one technical replicate. The endpoint was the bacterial load (CFU/ml) in the overnight supernatant, which was numerically lower for phage-treated membranes; no statistical test was performed because of the small number of repetitions. Agar imprints and light microscopy indicated less surface colonization after treatment, but these observations were qualitative. The study gives a preliminary indication that surface-associated phage T4 reduces the planktonic bacterial load, and possibly surface colonization, under the conditions tested. Quantification of the retained phage dose, a free-phage control, direct measurement of attached biomass and flow-through testing are priorities for further work.*

Keywords: *3D-printed membranes; bacteriophage T4; biofilm; water filtration*

1. INTRODUCTION

Biofilm formation on filtration membranes represents one of the most persistent and economically significant challenges in water treatment technology. Biofilms are structured communities of microorganisms embedded in a self-produced extracellular matrix that adhere to membrane surfaces and dramatically reduce filtration efficiency, increase hydraulic resistance, and accelerate membrane

fouling and degradation [1]. In membrane bioreactor (MBR) systems, biofouling is among the most costly operational problems, increasing energy consumption and shortening membrane lifespan [3]. Conventional mitigation strategies, including chlorination, UV irradiation, and chemical biocides, are effective but carry substantial drawbacks: they generate toxic by-products, contribute to the development and spread of antimicrobial resistance (AMR), and are incompatible with the principles of circular economy and sustainable development [2].

Bacteriophages (phages) are viruses that specifically infect and lyse bacterial cells. As obligate bacterial parasites, they offer highly targeted, self-amplifying biocontrol without chemical residues, making them promising candidates for next-generation anti-biofilm strategies [2]. Phage-based biofouling control has demonstrated practical efficacy in water treatment contexts: in an MBR system, treatment with lytic phage DTP1 restored membrane permeability to 70% of its original value within four days of application [3]. Bacteriophage T4, a well-characterised myovirus with broad lytic activity against *Escherichia coli*, is among the most extensively studied model phages for biofilm disruption research [4]. Its exceptionally large burst size and rapid replication cycle make it particularly suitable for continuous biofilm suppression in dynamic systems.

The integration of phages with solid surfaces—particularly 3D-printed membranes with customisable geometry-opens new possibilities for scalable, application-specific filtration solutions. Three-dimensional printing allows the production of membranes with defined pore architectures and surface chemistries that can be tailored to optimise phage retention and activity. Despite growing interest in phage-membrane hybrid systems, the systematic evaluation of 3D-printed substrates as geometrically customisable, low-cost platforms for phage T4 immobilisation in biofilm prevention remains largely unexplored. Strategies for phage immobilisation on solid surfaces, including physisorption and covalent binding via EDC/NHS chemistry or thiol-based self-assembled monolayers, have been reviewed in detail; maximising tail exposure of tailed phages is a key criterion for maintaining infectivity post-immobilisation [5].

The PhageGuard project is an interdisciplinary study conducted within the framework of the Problem-Based Learning programme at the University of Novo Mesto, co-funded by the Republic of Slovenia and the European Union under the European Social Fund Plus (ESF+). The project brought together students and staff from the Faculty of Economics and Informatics, the Faculty of Health Sciences, and the Faculty of Mechanical Engineering, in collaboration with the company CEROD d.o.o., to address a real-world biotechnological challenge – the prevention of biofilm formation in water filtration systems using biologically functionalized membranes. This paper reports the results of a pilot experiment evaluating the anti-biofilm efficacy of T4-functionalized 3D-printed membranes against *Escherichia coli (E. coli)*, quantified by colony-forming unit (CFU) counting and supported by microscopic analysis.

2. MATERIALS AND METHODS

Methodology approach of presented research is schematically represented in Figure 1.

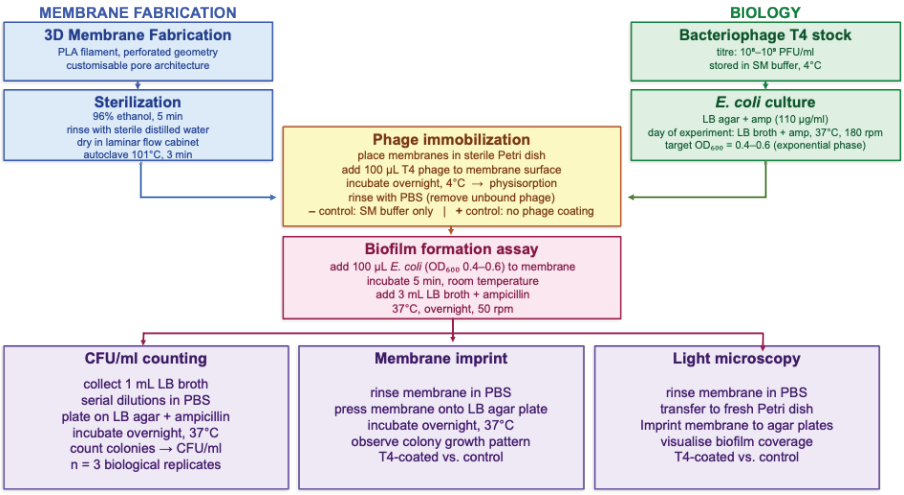


Figure 1: Schematic representation of the experimental workflow.

2.1. Microbial strain and phage stock

Bacteriophage T4 was obtained from Jafral d.o.o. (Slovenia) and stored in SM buffer at 4 °C. The titre of the stock was determined by the double-agar-overlay plaque assay and was 2.0×10^8 PFU/ml. The same stock was used in all experiments. A plaque assay was included as a control before each experiment to confirm phage viability; plates were compared visually with those of the preceding experiment and showed comparable plaque densities, but plaque counts were not recorded for individual runs, so no experiment-specific titres are available.

Escherichia coli (*E. coli*), donated by the Biotechnical Faculty, University of Ljubljana, and carrying a broad-host-range plasmid with a β-lactamase selection marker, was used as the model organism. The same strain was used in the phage titration and in all experiments; plaque formation on this strain confirms its susceptibility to phage T4. Bacterial cells from a −80 °C glycerol stock were streaked onto Luria–Bertani (LB) agar supplemented with ampicillin (final concentration 110 µg/ml) and grown overnight at 37 °C in the dark, without shaking. Ampicillin was included in all media and in all experimental groups to maintain selective pressure throughout the incubation and to suppress contamination and satellite colonies. Agar plates with grown *E. coli* colonies were stored at 4 °C until further use.

2.2. Membrane fabrication and phage immobilization

To provide a specific surface area suitable for both fluid passage and phage attachment, a defined perforated geometry was selected (Figure 2A). Membranes were fabricated from Polyethylene Terephthalate Glycol (PETG) using a Bambu Lab X1C 3D printer (Bambu Lab, China), with a nozzle temperature of 240 °C, a layer height of 0.2 mm, and 15 % infill. Each membrane had an overall diameter of 50 mm and a thickness of 3 mm. The perforation pattern consisted of circular pores (Ø 4.00 mm) arranged radially with a 5.55 mm spacing between successive pore rings along five radial arms positioned at 72° intervals, complemented by hexagonal openings spaced 10.00 mm apart (Figure 2A; all dimensions in mm), giving an exposed area of 14.38 cm² per face.

Before use, membranes were immersed in 96 % ethanol for 5 min, rinsed with sterile distilled water and dried in a laminar flow cabinet, then sealed in medical-grade sterilization pouches and heat-treated at 101 °C for 3 min. As this cycle does not correspond to a validated autoclave sterilization program, the procedure is described here as decontamination rather than sterilization. Membranes remained in the sealed pouches until immediately before use. Adequate decontamination was verified in every biological repetition by the phage-only control membranes, which were incubated in LB broth without added bacteria and showed neither turbidity nor colony growth on imprinting (Figure 3 A).

Phage immobilization was performed by physisorption [5]. Decontaminated membranes were placed in sterile Petri dishes (Figure 2 B) and 100 µl of the T4 stock, corresponding to approximately 2 × 10^7 PFU per membrane, was applied to the upper membrane surface and incubated overnight at 4 °C to allow passive adsorption. Negative-control membranes were treated identically with phage but received no bacteria; positive-control membranes received 100 µl of SM buffer instead of phage, with bacteria added in the following step. The next day, unbound phage particles were removed by a single wash: each membrane was briefly submerged in phosphate-buffered saline (PBS) with sterile forceps and transferred to a fresh sterile Petri dish, and the bacterial suspension was applied immediately afterwards. The phage retained after washing was not quantified. Under the batch conditions used here, phage desorbed from the membrane remains in the same small volume of broth as the membrane itself, so surface-associated and released phage cannot be distinguished.

Three membranes per experimental group were used in each biological repetition: one underwent the full analysis (supernatant quantification, imprinting and light microscopy), a second was additionally imprinted, and a third was retained for visual comparison of growth only.

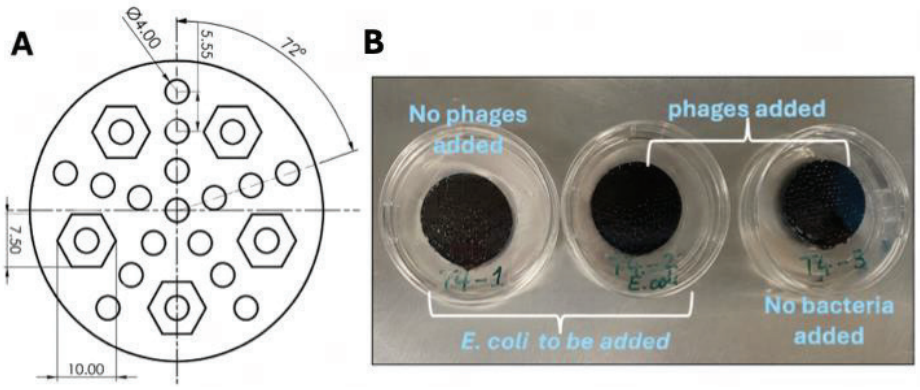


Figure 2: Membrane design and experimental setup.

A: Geometry of the 3D-printed PETG membrane, with circular pores (Ø 4.00 mm) arranged radially along five arms at 72° intervals and hexagonal openings spaced 10.00 mm apart; all dimensions in mm. **B:** The three experimental groups/conditions, photographed after membrane preparation and before bacterial inoculation: positive control (no phage adsorbed, *E. coli* to be added, left), T4-treated membrane (phage adsorbed, *E. coli* to be added, centre), and negative control (phage adsorbed, no bacteria, right).

2.3 Biofilm Formation Assay

Before each experiment, fresh colony of *E. coli* was inoculated in 20 ml of LB broth supplemented with amp (110 ug/ml) and grown at 37°C with shaking (180 rpm, revolutions per minute) until bacterial exponential growth phase was reached (Optical density OD_{600} = 0.4–0.6). At this stage, 100 uL of

E. coli was added to upper side of 3D-printed membranes that were already coated with 100 uL of T4 phage. As a positive control, 100 uL of *E. coli* were added to a membrane that were not coated with T4 (biofilm development/growth on membranes) and as a negative control, 100 uL of phage T4 was used for membrane coating and no bacterial cells were added (no biofilm development). After 5 minute incubation at room temperature, 3 ml of LB broth supplemented with ampicillin was added to each Petri dish, following incubation at 37 C, overnight, in dark, at 50 rpm.

2.4 Quantification of *E. coli* load and biofilm observation/confirmation

Following overnight incubation, 1 ml of the spent LB broth was taken from each Petri dish for quantification of planktonic *E. coli*. This endpoint represents surviving or growing cells in the supernatant and not biofilm biomass or viable cells attached to the membrane; it is therefore referred to throughout as supernatant CFU. Samples were serially diluted in PBS, and 100 µl of each dilution was plated on LB agar supplemented with ampicillin and incubated overnight at 37 °C. Only plates with 30–300 colonies were counted and the results expressed as CFU/ml (Colony Forming Units/ml); the resulting limit of quantification was 300 CFU/ml. Three independent biological repetitions were performed for all experiments, with a single technical replicate within each repetition, so within-experiment technical variability could not be estimated. A direct measurement of surface-associated biofilm, such as recovery of attached cells or quantitative image analysis, was not performed in this pilot experiment.

2.5 Membrane imprint and light microscopy

After the spent LB broth had been sampled, membranes were removed from the Petri dish and submerged in PBS to rinse off unbound bacteria and phage particles. After rinsing, membranes were imprinted onto LB agar plates to observe whether transferred bacterial cells were able to grow. No phage-neutralisation or separation step was included before imprinting, so the imprint reflects the combined effect of bacterial transfer and of any membrane-associated phage carried over onto the agar. The same membranes were subsequently examined by light microscopy.

Before microscopic analysis, membranes were rinsed once more and transferred into a fresh sterile Petri dish, then examined as native, unstained preparations with a KERN OKO 178 metallurgical light microscope (KERN & Sohn GmbH, Germany) under reflected (incident) illumination, using a total magnification 500×. Several positions on each membrane were examined, and a central field was recorded as representative. No quantitative image analysis, such as percentage area coverage, was performed, so the microscopic findings are reported as qualitative observations.

3. RESULTS

3.1. Bacterial load in supernatant

Bacterial counts (CFU/ml) in the overnight supernatants differed between the experimental groups. In Figure 3 A, more turbidity is observed in the Petri dish containing an untreated membrane with *E. coli* than in the dish in which phage had been adsorbed onto the membrane surface before the bacteria were added, while the dish containing phage only shows no turbidity, as only LB broth is present. Supernatant CFU in the untreated control group were 8.4×10^7, 9.0×10^7 and 5.2×10^7 CFU/ml in the three biological repetitions, and 1.68×10^5, 1.0×10^5 and 1.2×10^7 CFU/ml in the

T4 + *E. coli* group. Because the values span several orders of magnitude, data are summarized as the mean of $\log_{10}$-transformed counts with the standard deviation 7.86 ± 0.13 $\log_{10}$ CFU/ml for the untreated control and 5.77 ± 1.14 $\log_{10}$ CFU/ml for the T4 + *E. coli* group, a difference of 2.10 $\log_{10}$ (Figure 3 B). Supernatant CFU were numerically lower in the phage-treated group in all three repetitions, although the variability between repetitions was considerably greater in this group than in the control. Given the preliminary nature of the dataset, no formal statistical test was performed.

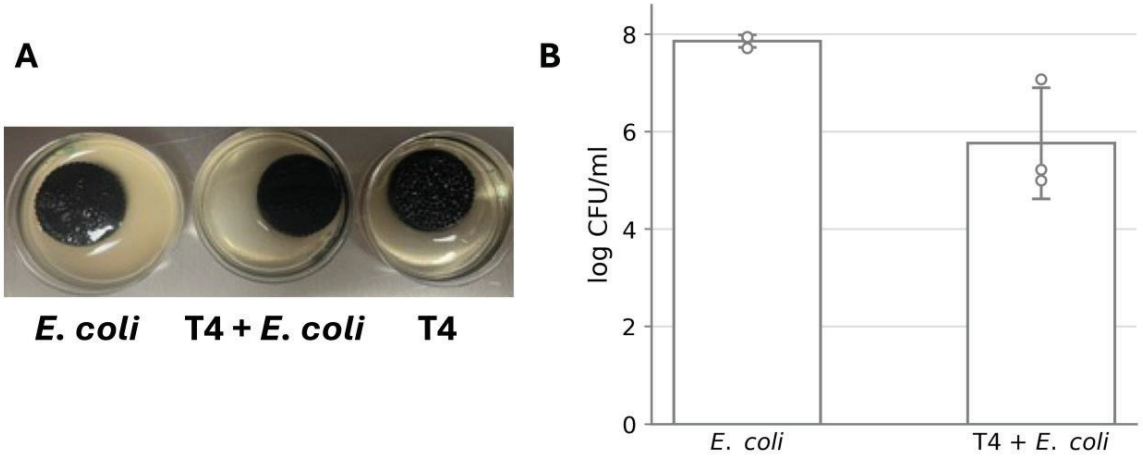


Figure 3: ***Quantification of supernatant E. coli growth following overnight incubation with T4-coated and uncoated 3D-printed membranes****. **A:** Petri dishes with a membrane showing the three experimental conditions – E. coli only (positive control, turbid broth), T4 + E. coli (experimental condition, visibly reduced turbidity), and T4 only (negative control, clear LB broth). **B:** bacterial load in the overnight supernatants expressed as $\log_{10}$ CFU/ml, shown as the mean with standard deviation of three biological repetitions; each circle represents one repetition. No statistical test was applied.*

3.2 Membrane imprint and light microscopy

Membrane imprints on LB agar revealed visible differences in colony-forming capacity between the two groups. Control membranes (*E. coli* only) consistently produced dense bacterial growth on the imprint agar plates, whereas phage-treated membranes produced visibly reduced colony density or no colonies in the majority of repetitions (Figure 4, center). As noted, this difference cannot be attributed to reduced bacterial attachment alone, since phage carried over with the membrane may also suppress colony formation on the agar. Light microscopy was consistent with the macroscopic observations: phage-treated membranes showed sparse individual bacterial cells with little surface coverage (Figure 4, left), while control membranes showed denser colonization with aggregates resembling early biofilm architecture (Figure 4, right). Two membranes were imprinted per agar plate, visible as two separate imprints on the plate on the right of the center panel. These observations were not quantified and are reported as qualitative.

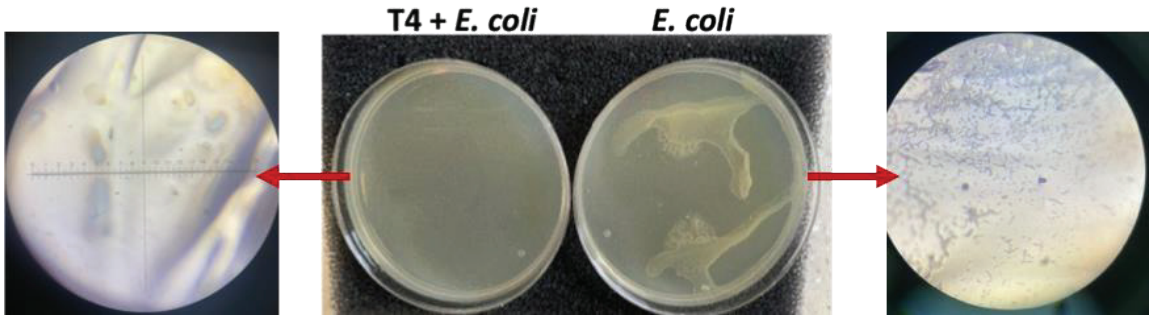


Figure 4: ***Comparative assessment of E. coli biofilm formation on T4-coated and uncoated membranes. Centre****: LB agar imprints after overnight incubation; the left plate is an imprint of a T4-treated membrane incubated with E. coli (no visible colony growth), the right plate an imprint of an untreated control membrane (E. coli only, colony growth across the agar surface). Red arrows indicate the corresponding membrane surfaces examined by light microscopy.* ***Left micrograph*** *(T4-treated membrane): sparse individual bacterial cells with minimal surface coverage.* ***Right micrograph*** *(untreated control): denser colonization with aggregates consistent with early biofilm formation. Total magnification 500×. The images are representative of three biological repetitions; no quantitative image analysis was performed.*

4. DISCUSSION

This pilot study provides a preliminary indication that T4-functionalized 3D-printed membranes are associated with a lower planktonic *E. coli* load, and possibly with less surface colonization, under used contitions. The lower supernatant CFU and the qualitative microscopy findings are consistent in direction with the published literature on phage-mediated biofilm control [2, 3, 4]. Our observations are compatible with the hypothesis that surface-associated bacteriophages retain sufficient lytic activity to limit bacterial growth near the membrane *in vitro*, although the contribution of immobilized and released phage cannot be separated in this design.

The inter-replicate variability in the T4 + *E. coli* group may reflect heterogeneous phage coating density across membrane surfaces, non-optimal phage binding or orientation, desorption during washing, or variable contact between phage particles and bacteria during batch incubation. Variation in the bacterial inoculum, in the phage titre, between individual printed membranes, and in pipetting, dilution and plating may have contributed as well. None of these factors was measured directly, so their relative contribution cannot be assessed, and the multiplicity of infection could not be calculated because neither the retained phage dose nor the exact inoculum was quantified. Supernatant CFU in this group spanned two orders of magnitude (from 1.0×10^5 to 1.2×10^7 CFU/ml), in contrast to the narrow range of the untreated control group. CFU data alone cannot establish the degree of phage surface coverage, so this pattern is only suggestive of uneven immobilization. Optimization of the immobilization protocol is therefore a priority for future work. As reviewed by O'Connell et al. [5], covalent binding methods such as EDC/NHS coupling or thiol-based self-assembled monolayers provide more stable and orientationally controlled phage attachment than physisorption.The use of 3D-printed membranes in this study offers practical advantages beyond experimental tractability. Additive manufacturing enables the production of membranes with precisely controlled pore geometry and surface-to-volume ratios, which are critical parameters for both hydraulic performance

and phage retention. Future work of the PhageGuard design could incorporate surface functional groups (e.g., amino or carboxyl modifications) to enhance covalent phage immobilization and potentially extend functional lifetime.

The wider relevance of phage-based biofilm control lies in its compatibility with several principles of the circular economy. Unlike chemical biocides, phages are self-amplifying in the presence of a susceptible host, are proteinaceous and therefore biodegradable, and do not generate halogenated by-products; their reported host specificity limits non-target effects [2]. Reyneke et al. [2] argue that phage biocontrol could be applied across the consumer water cycle, with a potential additional benefit for the environmental burden of antimicrobial resistance (AMR). Realizing this potential will require attention to several factors: amplification depends on a susceptible host, lysis releases endotoxin and cellular material into the treated water, and phage resistance, non-target effects, biosafety and environmental persistence all require evaluation. A further barrier is the absence of a dedicated EU regulatory framework for the environmental application of bacteriophages. Finally, PhageGuard illustrates that phage-based biofilm control requires the convergence of disciplines that rarely intersect in water treatment research and underscores the value of interdisciplinary problem-based learning.Limitations of this study include the use of a single model organism, and the absence of flow-through conditions representative of real filtration systems. Future work will address these limitations by incorporating phage-membrane performance under dynamic flow conditions and with mixed bacterial communities.

5. CONCLUSION

This study p‹ovides a preliminary indication that bacteriophage T4-functionalized 3D-printed membranes are associated with a lower planktonic *E. coli* load. Supernatant CFU were lower in the phage-treated group in all three biological repetitions, corresponding to a difference of 2.10 $\log_{10}$ CFU/ml between group means (5.77 ± 1.14 versus 7.86 ± 0.13 $\log_{10}$ CFU/ml), and agar imprints and light microscopy pointed in the same direction, although these observations were qualitative. Given the small number of repetitions, the absence of statistical testing and the considerable variability between repetitions, the findings should be regarded as an early indication rather than a demonstration of efficacy, but they justify continued development of phage-membrane hybrid systems. The PhageGuard project, in which the experimental work was carried out by students from three faculties, illustrates the potential of interdisciplinary Problem-Based Learning to address real-world environmental and engineering challenges within an academic setting.

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Original scientific paper

PROFESSIONAL SATISFACTION AMONG CROATIAN FIREFIGHTERS: THE ROLE OF SOCIAL SUPPORT AND COPING STRATEGIES WITHIN THE JD–R FRAMEWORK

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Abstract: *Firefighting is a high-risk occupation characterized by exposure to stressful and traumatic events. Guided by the JD–R model, this study examined predictors of professional satisfaction among 267 Croatian firefighters. Social support, coping strategies, and professional satisfaction were assessed using self-report measures. Intrinsic and relational aspects of firefighting were rated as the most important sources of satisfaction, whereas organizational aspects were rated lower. Hierarchical regression identified social support as the strongest positive predictor of professional satisfaction (β = .360, p < .001), followed by adaptive coping (β = .232, p = .002). Avoidant coping (β = –.160, p = .025) and years of service (β = –.172, p = .007) were negative predictors. Support from supervisors and friends emerged as significant predictors. The findings highlight the importance of social and personal resources for sustaining professional satisfaction among firefighters.*

Keywords: *firefighters; professional satisfaction; social support; coping strategies; JD–R model*

1. INTRODUCTION

Firefighting is a high-risk occupation characterized by frequent exposure to stressful and potentially traumatic events, including serious injuries, fatalities, and large-scale disasters. Research has consistently documented elevated rates of post-traumatic stress symptoms, burnout, depression, and suicidal ideation among firefighters compared to the general population [1,2]. While previous studies have predominantly focused on adverse mental health outcomes, considerably less attention has been devoted to factors that contribute to firefighters' professional satisfaction and well-being.

The Job Demands–Resources (JD–R) model provides a useful framework for understanding occupational well-being [3,4]. According to the model, job resources and personal resources contribute to positive work outcomes through a motivational process. Social support represents one of the most important job resources and has been associated with reduced burnout, increased engagement, and greater organizational connectedness among firefighters [5,6]. Coping strategies can be viewed as personal resources that influence individuals' ability to manage occupational

demands. Adaptive coping strategies are generally associated with better psychological adjustment, whereas avoidant coping is linked to poorer well-being outcomes [7,8].

Although the JD–R motivational process has been examined in relation to engagement and burnout among firefighters, professional satisfaction has received comparatively limited empirical attention. Understanding the factors associated with professional satisfaction may provide valuable insights for promoting occupational well-being in this high-risk profession.

The present study aimed to examine predictors of professional satisfaction among Croatian firefighters within the JD–R motivational process framework. Specifically, we investigated whether perceived social support and coping strategies predicted professional satisfaction beyond years of service and type of firefighting unit. Additionally, we examined whether different sources of social support contributed differentially to professional satisfaction.

2. MATERIALS AND METHODS

2.1. Participants and Procedure

A cross-sectional online survey was conducted among Croatian firefighters between June 2023 and June 2025. The questionnaire was distributed through county-level fire brigades and firefighting-related social media groups. Participation was voluntary and anonymous, and informed consent was obtained electronically before participation.

The final sample included 118 professional firefighters employed in public fire brigades (PFF; 44.2%) and 149 volunteer firefighters (VFF; 55.8%). Mean job tenure was 12.4 years (SD = 9.9; range = 1–38). Age was excluded from further analyses due to a high proportion of missing responses (19%), and years of service were used as an indicator of professional experience.

The study was approved by the Ethics Committee of the Faculty of Forensic Sciences, University of Split (11 April 2022; Class: 025-03/22-03/20; Ref. No.: 2181-227-102/1-22-3).

2.2. Measures

Professional satisfaction was assessed using a firefighter-specific questionnaire developed by Pavlić [9]. The instrument comprises 17 items assessing organizational, relational, and intrinsic sources of satisfaction, rated on a five-point scale (1 = not a source of satisfaction at all; 5 = an extremely important source of satisfaction). An overall professional satisfaction index and three domain-specific indices were calculated. Internal consistency was satisfactory to excellent (α = .827–.918).

Perceived social support was assessed using four items measuring satisfaction with support received from family, colleagues, supervisors, and friends [9]. Responses were provided on a five-point scale, and a composite score was calculated as the mean of all items (α = .748).

Coping strategies were assessed using the Brief COPE Inventory [8]. Exploratory factor analysis supported a two-factor solution distinguishing adaptive and avoidant coping (KMO = .908; Bartlett's $\chi^2 = 3965$, $p < .001$), explaining 42.4% of the variance. Problem-focused and emotion-focused item families were combined into an adaptive coping composite, whereas avoidance/disengagement-oriented items were combined into an avoidant coping composite. Internal consistency was excellent for adaptive coping (α = .924) and good for avoidant coping (α = .847).

3. RESULTS

3.1. Sources of professional satisfaction

Firefighters derived the greatest satisfaction from intrinsic and relational aspects of their work: helping people (M = 4.62), sense of accomplishment (M = 4.48), and gratitude from victims (M = 4.30). Organizational aspects received lower ratings, with salary (M = 2.67) and work schedule (M = 3.11) at the bottom (Figure 1). Professional and volunteer firefighters reported comparable overall satisfaction (M = 3.81 vs. 3.82, p = .756). After FDR correction, only salary and work schedule differed significantly, both rated higher by professional firefighters (p < .001).

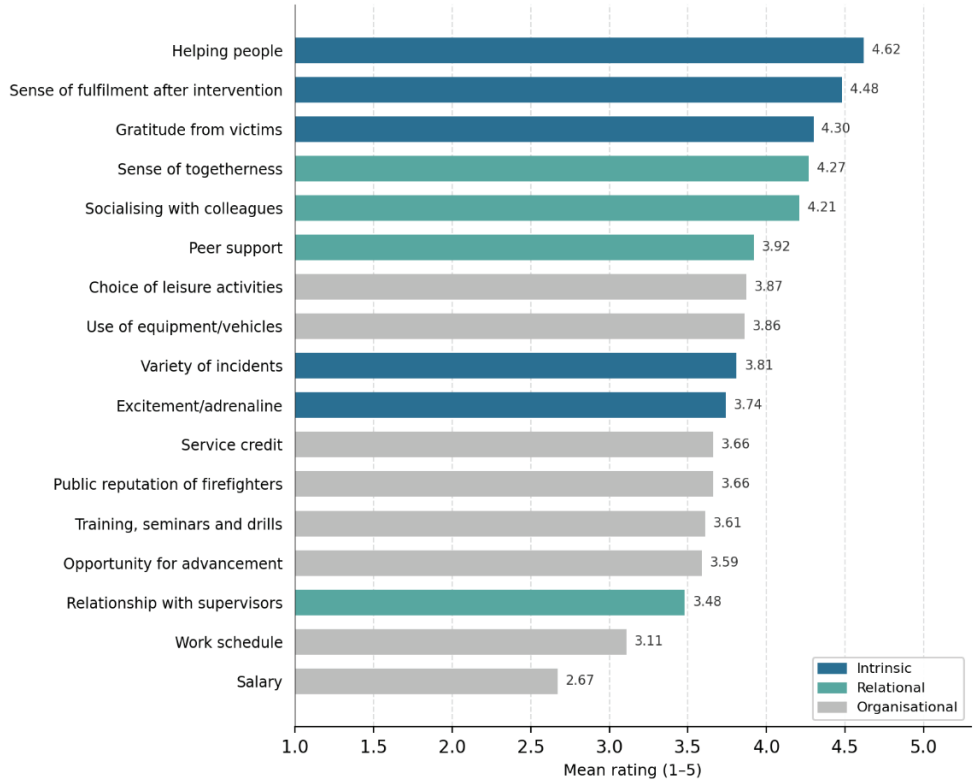


Figure 1: Mean ratings of professional satisfaction sources by category (N = 267). Items ordered from highest to lowest. Dark = intrinsic; medium = relational; light = organizational. Scale: 1–5.

3.2. Predictors of professional satisfaction

A hierarchical regression examined predictors of overall satisfaction (Table 1). In Step 1, years of service and unit type explained 5.5% of the variance (R^2 = .055, p = .004). Adding social support in Step 2 substantially increased the explained variance (ΔR^2 = .154, p < .001). Adding coping strategies in Step 3 significantly increased the explained variance (ΔR^2 = .040, *F*change(2, 261) = 6.94, *p* = .001). The final model was statistically significant (p < .001). The incremental variance at each step is shown in Figure 2.

The final model was significant, F(5, 261) = 13.15, p < .001, R^2 = .248. Social support was the strongest positive predictor (B = 0.376, β = .360, p < .001), followed by adaptive coping (B = 0.244, β = .232, p = .002). Avoidant coping (B = −0.234, β = −.160, p = .025) and years of service (B = −0.012, β = −.172, p = .007) were negative predictors. Unit type was not significant (p = .306).

Table 1: Hierarchical regression predicting overall professional satisfaction (N = 267)

Predictor	B	SE	β	t	p	R^2
Step 1						
Years of service	−0.017	0.005	−.235	−3.35	<.001	
Unit type (PFF)	0.025	0.085	.018	0.29	.768	
Model					.004	.055
Step 2						
Social support	0.415	0.063	.397	6.58	<.001	
Model					<.001	.209
ΔR^2					<.001	.154
Step 3						
Social support	0.376	0.063	.360	5.95	<.001	
Adaptive coping	0.244	0.077	.232	3.16	.002	
Avoidant coping	−0.234	0.105	−.160	−2.24	.025	
Years of service	−0.012	0.005	−.172	−2.70	.007	
Unit type (PFF)	0.080	0.079	.057	1.02	.306	
Model					<.001	.248
ΔR^2					.001	.040

Note. OLS regression with HC3 standard errors. β = standardized coefficient. Unit type: 1 = PFF, 0 = VFF. Durbin–Watson = 1.97.

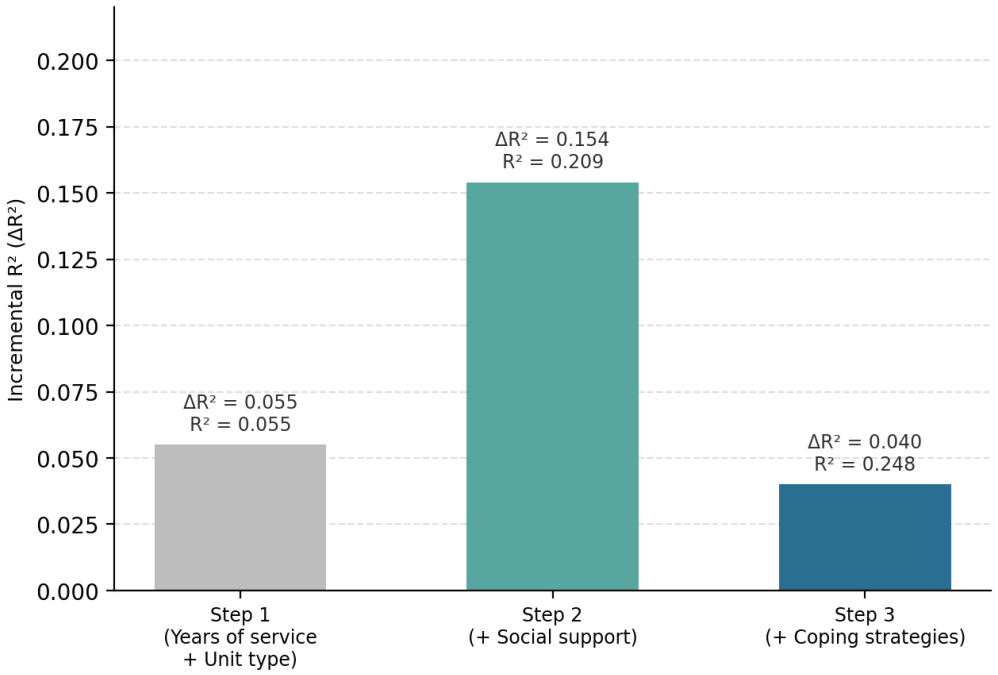


Figure 2: Incremental variance explained (ΔR^2) at each step of the hierarchical regression. Step 1: years of service + unit type. Step 2: + social support. Step 3: + coping strategies. Final R^2 = .248.

3.3. Differential contribution of social support sources

A supplementary regression examined whether the four sources of support differentially predicted satisfaction (Table 2). Support from supervisors (B = 0.126, β = .197, p < .001) and friends (B = 0.158, β = .181, p = .007) were significant, whereas colleagues (p = .268) and family support (p = .971) were not. Adaptive and avoidant coping remained significant (R^2 = .259).

Table 2: Regression with separate sources of social support as predictors (N = 267)

Predictor	B	SE	β	t	p
Supervisor support	+0.126	0.037	.197	3.39	<.001
Friend support	+0.158	0.059	.181	2.69	.007
Colleague support	+0.083	0.075	.093	1.11	.268
Family support	−0.002	0.049	−.002	−0.04	.971
Adaptive coping	+0.264	0.079	.251	3.33	<.001
Avoidant coping	−0.245	0.105	−.167	−2.33	.020
Years of service	−0.011	0.005	−.158	−2.38	.018
Unit type (PFF)	+0.098	0.079	.069	1.25	.213
Model R^2	.259				<.001

Note. OLS regression with HC3 standard errors. β = standardized coefficient. R^2 = .259.

4. DISCUSSION

The findings are consistent with the JD–R motivational process by demonstrating the importance of both occupational and personal resources for professional satisfaction among firefighters. Social support emerged as the strongest positive predictor of professional satisfaction, followed by adaptive coping strategies, whereas avoidant coping and longer years of service were associated with lower satisfaction. These findings align with the JD–R framework, which emphasizes the role of job and personal resources in promoting positive work outcomes and sustaining occupational well-being [4].

The importance of social support aligns with previous research highlighting its protective role in firefighting populations. Evidence suggests that social support serves as a protective function among firefighters by buffering the effects of occupational demands and promoting organizational engagement and retention [5,6]. Interestingly, support from supervisors and friends emerged as significant predictors in the present study, whereas support from colleagues and family did not. This finding suggests that both organizational and extra-occupational sources of support may play a role in maintaining professional satisfaction.

Firefighters reported the highest levels of satisfaction with the intrinsic and relational aspects of their work, particularly helping others and experiencing a sense of accomplishment after successful interventions. In contrast, organizational aspects such as salary and work schedule received comparatively lower ratings. This pattern is consistent with previous findings emphasizing the importance of meaning, purpose, and prosocial contribution in firefighting work [10].

Several limitations should be acknowledged. The cross-sectional design precludes causal inference, and the use of self-report measures may have introduced common method bias. Furthermore, the convenience sampling approach limits the generalizability of the findings. Future studies should employ longitudinal designs and examine additional occupational and personal resources within the JD–R framework.

5. CONCLUSION

Social support and adaptive coping were positively associated with professional satisfaction among Croatian firefighters, whereas avoidant coping and longer years of service were negatively associated with satisfaction. The findings are consistent with the JD–R motivational process and highlight the importance of social and personal resources in high-risk occupations. Strengthening supportive relationships and promoting adaptive coping strategies may contribute to firefighters' occupational well-being.

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Note on Data Source

The dataset used in this study was originally collected for the second author's master's thesis. The present paper reports a secondary analysis to examine predictors of professional satisfaction among firefighters.

The same dataset has also been used in a separate manuscript currently under review in *Occupational Medicine*, addressing different research questions related to the health-impairment process of the JD–R model.

Original scientific paper

FUNCTIONAL DESIGN OF A PROTECTIVE FIREFIGHTER COVERALL

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Abstract: *This paper examines the ergonomic aspects of designing protective coveralls for fire service personnel, with particular emphasis on how dynamic body movements affect the comfort, mobility, and functionality of protective clothing. For the purposes of the research, a survey was conducted among end users to identify their experiences, needs, and perceived shortcomings of existing protective coveralls. Based on the survey results, a functional design for a protective coverall was proposed to improve comfort, safety, and freedom of movement during firefighting operations.*

Keywords: *firefighter coverall, functional design, ergonomics, dynamic anthropometry, protective clothing*

1. INTRODUCTION

Firefighting is an activity focused on preventing fires and explosions, suppressing fires, rescuing people and property, and intervening in hazardous situations. Protective clothing plays a key role in providing protection against heat, flames, moisture, and mechanical injuries, while simultaneously enabling unrestricted movement and a high level of comfort. As it is worn during long-lasting and physically demanding interventions, its ergonomics directly affect user fatigue, safety, and efficiency [1].

High-quality personal protective equipment must comply with technical requirements, be designed to protect against specific hazards without introducing new risks, and be adapted to real working conditions [2]. Materials that may melt at high temperatures and cause additional skin injuries present a particular challenge, which is why materials with enhanced protective properties are used in the production of firefighting garments. The development of advanced textile materials and membrane systems has reduced garment weight while improving mobility and comfort, without compromising protective performance [3].

In protective clothing design, dynamic anthropometry plays an important role as a basis for analysing changes in human body dimensions during movement. Its application in protective garment design is reflected in predicting garment behaviour in different body positions, with the aim of reducing movement restriction and local stress [1,4]. The ergonomic approach encompasses interdisciplinary knowledge aimed at optimising safety, functionality, and comfort within the working system. In the context of protective clothing, ergonomics is particularly important as it represents a direct interface between the user and external hazards and must enable the uninterrupted performance of work tasks [4]. When designing protective clothing, it is necessary to consider both static and dynamic anthropometric data, as well as the biomechanical characteristics of the human body [4].

A high level of protection is achieved through the selected materials and the synergy of all elements of the clothing system, which together form a complete protective system. Protective clothing systems consist of multiple components designed to protect individual body segments, and firefighting garments may be designed as one-piece (coveralls) or two-piece systems. Comfort and functionality are essential properties that the system must provide, both from a structural design perspective and from the perspective of the materials used [5].

Studies on the ergonomic aspects of two-piece firefighter protective clothing indicate that users frequently report the need for improvements in functional and structural characteristics. The results also highlight issues related to comfort, mobility, and garment fit [1, 4].

Fit and comfort problems arise from the dynamic nature of the human body and significant differences between static and dynamic anthropometric measurements. During certain movements, clothing may restrict the range of motion, potentially compromising functionality and safety during firefighting operations. Dynamic anthropometry therefore makes an important contribution to improving comfort and mobility, particularly in complex multi-joint movements [5, 6].

An additional challenge concerns the definition of appropriate sizing systems for firefighter protective clothing. Hsiao et al. emphasise the need to adapt sizing systems to the actual user population [7].

Proper garment sizing and fit are essential for ensuring mobility, comfort, and the ergonomic functionality of protective clothing [5].

The aim of this study is to analyse the influence of body movements on the ergonomic properties of firefighter protective coveralls and, based on the findings obtained, to propose an improved solution that contributes to greater safety, comfort, and functionality of the firefighter coverall.

2. METHODS

A structured questionnaire with 42 questions was used, divided into four thematic sections. The first section covered basic anthropometric and demographic data of the respondents (age, body height, and body weight). The second section addressed the selection of the protective firefighter coverall size and satisfaction with the chosen size. The third section focused on a subjective ergonomic assessment of the fit, comfort, and functionality of the protective coverall during work. The fourth section included an ergonomic assessment of mobility, as well as the identification and recording of any physical discomfort experienced during specific work movements and tasks.

At the end of the questionnaire, respondents could provide open comments, suggestions, and recommendations for improving the ergonomic and functional characteristics of the firefighter coverall.

The questionnaire comprised both closed and open-ended questions, enabling quantitative and qualitative analysis of user experiences.

Based on the results obtained, key ergonomic issues were identified and guidelines were defined for proposing a functional design of the protective firefighter coverall.

The figures presented in this paper are adapted from the author's graduate thesis [8].

3. RESULTS AND DISCUSSION

The survey included 37 professional firefighters employed by the Zagreb Public Fire Brigade. According to the results of the first section of the questionnaire, all respondents were male, aged between 18 and 46 years. The average body height was 180.81 cm, and the average body weight was 90.31 kg. The age distribution of the respondents is shown in Fig. 1.

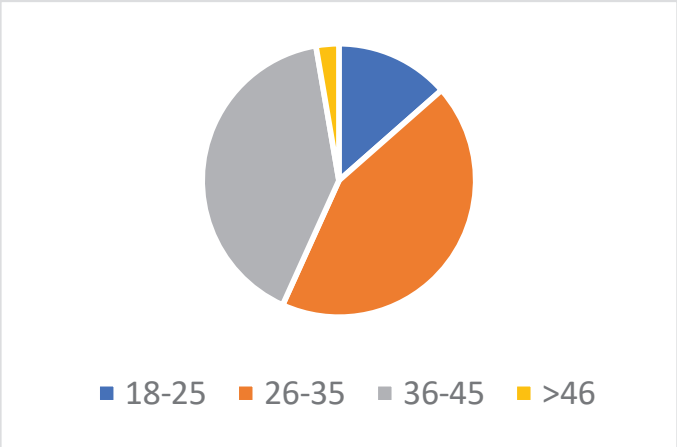


Figure 1: Age distribution of respondents

The second section of the questionnaire focused on the selection of protective coverall sizes. Most respondents chose a coverall size corresponding to their usual ready-to-wear clothing size, provided that the same size was suitable for both the upper and lower body. When different sizes were required, preference was generally given to the lower body size. This finding is understandable, as an inappropriate fit in the hip and leg area can considerably restrict mobility and flexibility, both of which are essential during firefighting interventions. The distribution of selected garment sizes for the upper and lower parts of the coverall is shown in Fig. 2.

A total of 18 respondents (48.6%) reported that the final size selection was made only after trying several sizes, taking into account their own perception of comfort, recommendations from experienced colleagues, and the specific requirements of their work. These findings indicate that selecting the most appropriate garment size is not a straightforward process, but depends on individual anthropometric characteristics and practical experience.

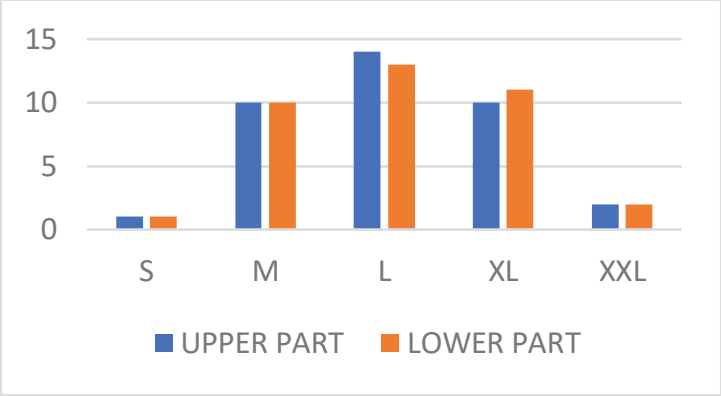


Figure 2: Distribution of selected coverall sizes

The third section of the questionnaire addressed the subjective ergonomic evaluation of the protective coverall, including comfort, garment fit, adaptability to the body, and the functionality of constructional elements such as sleeve and trouser dimensions, as well as the position, size, and number of pockets.

The respondents generally expressed a moderately positive opinion regarding the comfort of the protective coverall. Overall, 54% of the respondents rated the coverall as comfortable or very comfortable, whereas 8.1% considered it uncomfortable or very uncomfortable. The remaining respondents expressed a neutral opinion (Fig. 3).

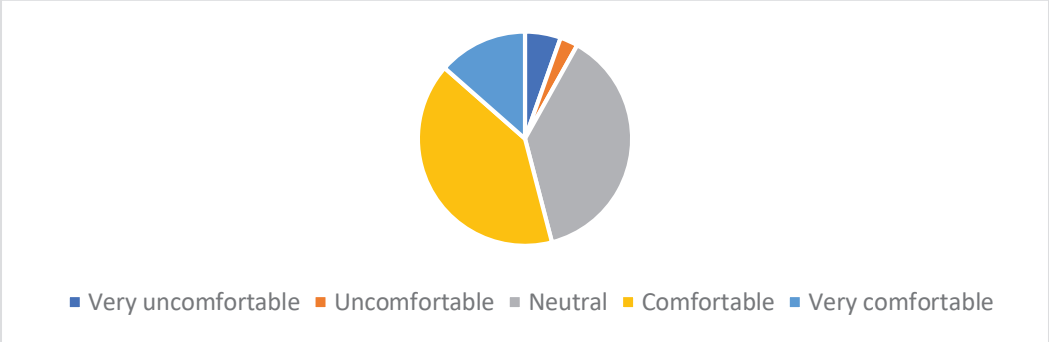


Figure 3: Subjective assessment of coverall comfort

Although most users assessed the overall comfort positively, several shortcomings were identified in the open-ended responses. The most frequently reported problem was the material's inadequate waterproofing, which allows moisture to penetrate during firefighting operations, reduces thermal comfort, and consequently affects firefighters' operational readiness, particularly during winter interventions. Respondents also highlighted several construction-related deficiencies, including excessively wide sleeves, suspender buckles positioned on the inner side of the coverall, and knee reinforcement of insufficient length. Wide sleeves were reported to interfere with precise and rapid arm movements, the suspender buckles caused discomfort during prolonged wear, and the knee reinforcement seam was positioned directly over the knee when kneeling, increasing local pressure and discomfort.

The survey further revealed that 56.7% of respondents had experienced damage to their protective coveralls during operational use. The most common forms of damage included seam failure, tearing

of the protective reinforcement at the knees, damage to retroreflective strips, abrasion of sleeve materials, and mechanical damage caused by contact with firefighting equipment such as axes and chainsaws. These findings indicate that, in addition to ergonomic improvements, greater attention should be devoted to enhancing the durability of highly exposed parts of the protective garments.

The subjective assessment of garment fit showed that 64.9% of respondents rated the fit as good or very good (Fig. 4). Although these results indicate overall satisfaction with the fit, the previously identified construction shortcomings suggest that further improvements are required to achieve optimal ergonomic performance.

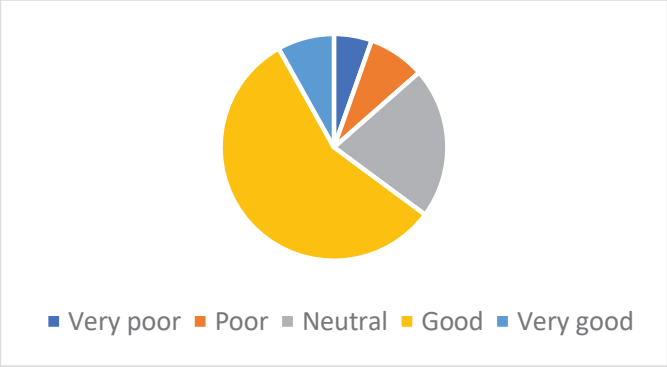


Figure 4: Subjective assessment of coverall adjustability

The fourth section of the questionnaire focused on mobility during typical firefighting movements and on identifying body regions where the coverall caused discomfort or restricted movement. While wearing their standard protective coveralls, the respondents performed a series of movements representative of firefighting activities, including raising the arms to shoulder height, including raising the arms with elbow flexion, raising both arms above the head, placing the hands behind the neck, shoulder rotation, squatting, trunk flexion, kneeling, knee flexion, side stepping, lifting a load from the ground, walking in a squatting position, crawling, and standing up quickly from a lying position. During each movement, the respondents recorded any perceived garment tightening and restriction of movement.

The results related to garment tightening are presented in Fig. 5.

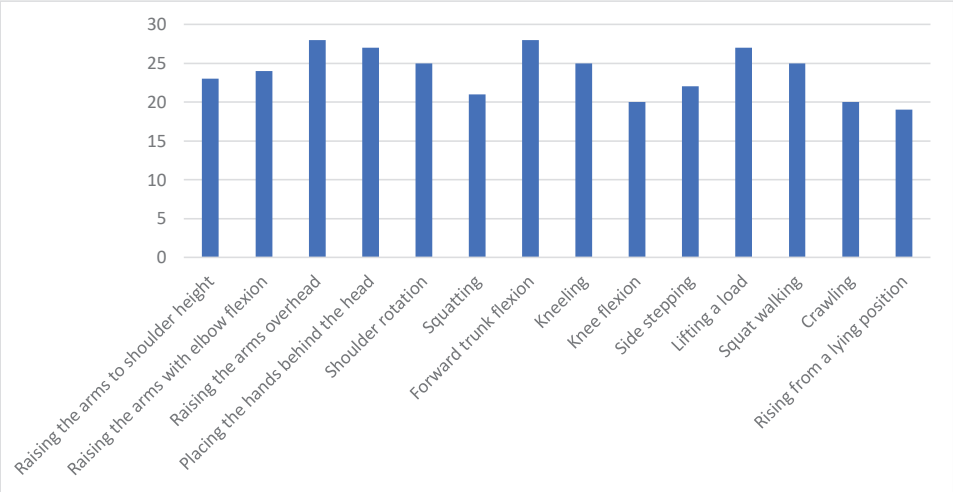


Figure 5: Frequency of perceived garment tightening during different body movements

More than half of the respondents reported noticeable tightening during all the movements analysed. The lowest frequency of tightening was observed when standing up from a lying position (51%), followed by knee flexion and crawling (54%), squatting (56.8%), side lunges (59.5%), raising the arms and elbow flexion (64.9%), and raising the arms to shoulder height (62%). The highest frequency of tightening was recorded during shoulder rotation, kneeling, and walking in a squatting position (67.6%), while the greatest discomfort was reported when placing the hands behind the neck and lifting a load (73.9%), as well as when raising both arms above the head and bending the trunk forwards, where tightening was reported by 75.7% of the respondents.

The perceived restriction of movement during the activities performed is shown in Fig. 6. The greatest limitation of mobility was reported during side lunges (35%), followed by squatting and standing up from a lying position (32.4%). Kneeling and walking in a squatting position limited movement in 29.7% of respondents, while knee flexion and crawling caused movement restriction in 27% of respondents. The remaining movements analysed resulted in mobility limitations for approximately 24.3% of respondents.

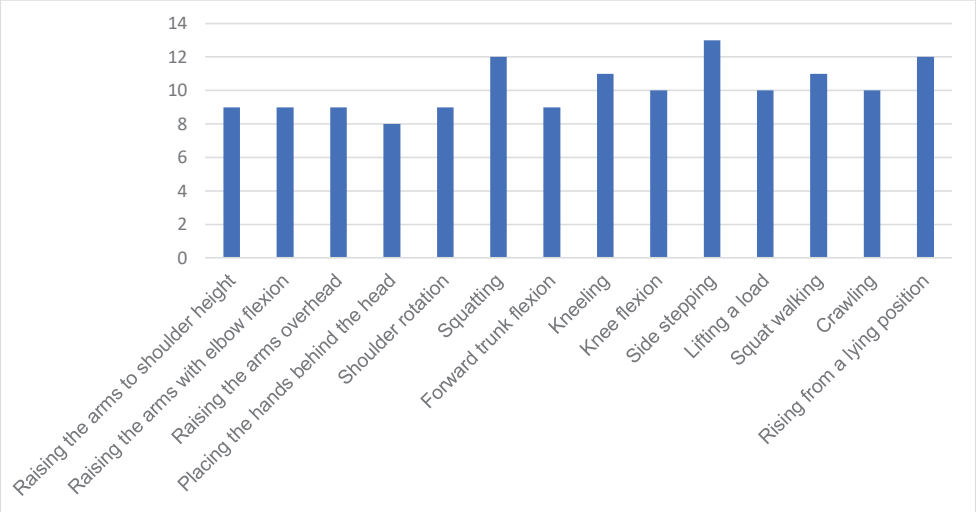
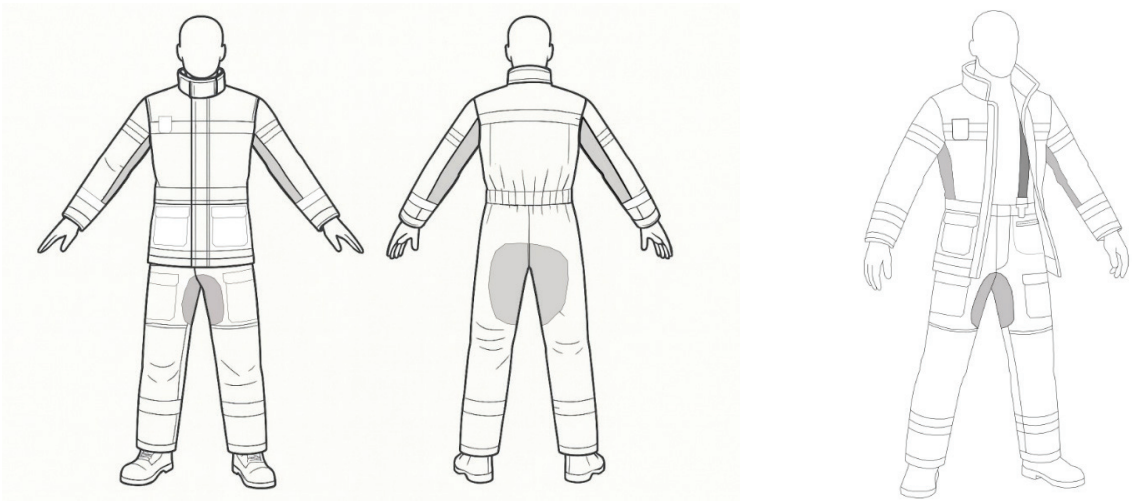


Figure 6: Frequency of perceived movement restriction during different body movements

In the open-ended part of the questionnaire, respondents proposed several improvements to enhance the functionality of the protective coverall. The most frequently suggested modifications included more effective waterproof materials, additional reinforcements in the knee and elbow areas to increase abrasion resistance, a waterproof pocket for personal belongings, and extra pockets for carrying equipment such as a portable radio and flashlight. A two-way front zip was also identified as a desirable design feature to improve usability during operational tasks [8].

Based on the survey findings and with reference to the relevant standards for firefighter protective clothing, a new functional design of the firefighter protective coverall was developed.

The primary objective of the proposed design is to enhance firefighters' comfort, mobility, and functionality while maintaining a high level of protection. The proposed coverall is conceived as an integrated one-piece garment that combines the upper and lower sections into a single construction, thereby reducing the possibility of heat, smoke, or water penetrating through the junction between separate garments (Fig. 7).



a) b)

Figure 7: Proposed firefighter protective coverall: a) front and back views of the closed coverall; b) front view of the open coverall

The upper part of the coverall is designed as a jacket with a raised collar that provides additional protection for the neck area and reduces the penetration of hazardous substances towards the upper body. The jacket opens at the front, facilitating rapid dressing and undressing during emergency situations. Unlike conventional two-piece systems, the back section remains permanently connected to the lower part of the coverall, ensuring continuous protection throughout the intervention. The front opening is secured with a combination of a zip and hook-and-loop fastener .

4. CONCLUSION

The survey results indicate a need for improvements in the design of firefighter protective coveralls, primarily to increase comfort, freedom of movement, and the functionality of individual construction elements. Based on respondents' feedback, a functional coverall design was proposed that retains the characteristics of the existing model which firefighters identified as beneficial during operational use.

The proposed design incorporates ergonomic modifications and additional functional features intended to facilitate movement and improve usability while maintaining the required level of protection. Particular emphasis was placed on enhancing the adaptability of the coverall to different body shapes, improving mobility during typical firefighting movements, and increasing the durability of highly exposed areas without compromising protective performance.

The proposed firefighter protective coverall is expected to improve user comfort, reduce physical strain and fatigue during interventions, and contribute to greater operational efficiency and safety. Furthermore, the findings demonstrate the importance of a systematic user-centred approach to the development of protective clothing, in which ergonomic analysis and feedback from end users provide essential information for optimising functional and construction design solutions.

Acknowledgements

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Professional paper

INTEGRATED FIRE ALARM SYSTEM RESPONSE THROUGH MODULES AND BUILDING SAFETY INTERFACES

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Abstract: *This paper analyzes integrated fire alarm system operations via interface modules to enhance building automation and occupational safety. Upon detector activation, the system transmits signals or actuates dry contacts via its modules to trigger smoke extraction, lower smoke curtains, and isolate hazards by closing HVAC dampers. In Ex-zones, Zener barriers ensure intrinsically safe operation, while short-circuit isolators protect overall loop integrity. Simultaneously, elevators recall to the ground floor, escalators stop, access control doors unlock, and voice alarm systems broadcast emergency evacuation instructions. This coordinated response significantly enhances life safety and property protection during fire emergencies.*

Keywords: *fire detection and alarm system, fire alarm modules, smoke control, building automation, occupational safety*

1. INTRODUCTION

Fire is one of the greatest hazards in the workplace, requiring an immediate and flawless response. Smoke, flames and toxic gases can rapidly endanger workers' lives, causing respiratory injuries, burns, or panic during evacuation. Research and historical statistics show that human perception and decision-making under conditions of extreme stress, reduced visibility, and toxic smoke are often delayed or inadequate [1]. Therefore, it is crucial to have an automated fire protection system that not only detects fire but also immediately initiates coordinated safety protocols.

The safety of modern facilities, from high-rise office buildings to complex industrial plants, relies heavily on advanced automation.

The primary function of fire protection has evolved from simple detection to managing complex safety interfaces across various building subsystems.

A fire alarm system is no longer a simple "alarm"; it has become a central processing unit managing mechanical and electrical subsystems. The scope encompasses smoke extraction control, area isolation, Ex-zone intrinsic safety, vertical transport shutdown and automated voice

evacuation protocols. This work contributes a comprehensive overview of how automated module-driven integration supports occupational safety and health (OSH) compliance and reduces risks to human life during emergency evacuations.

2. INTEGRATED SYSTEM ARCHITECTURE AND RESPONSE FUNCTIONS

2.1. Fundamentals of fire alarm systems: control panel and addressable technology

Modern fire alarm systems, particularly those installed in larger or more complex facilities, often use addressable technology, in which each device has a unique address on the communication loop.

Detectors (automatic or manual) are installed throughout the facility. When a detector is activated, it sends a signal to the fire alarm control panel (FACP) – the main device monitoring the entire system. The panel receives the signal, verifies it, and decides whether to activate the alarm. It then sends commands to other parts of the system via specialized modules, including a signal to the electrical cabinet.

This automation is vital for occupational safety. Workers often operate in enclosed spaces where smoke fills the room quickly and reduces visibility. Rapid signal processing and the automatic activation of safety functions provide workers with more time for safe evacuation, reduce the risk of asphyxiation and injury and prevent the fire from spreading. This directly protects the health and lives of employees in the workplace.

2.2. The role of input/ output (I/O) modules

Modules serve as the critical link between the control panel and controlled devices and systems (often part of the building's power systems):

- **output relay modules:** provide volt-free contacts to other systems (e.g., for shutting down ventilation or AC switches)
- **monitored output modules:** used where it is necessary to constantly monitor the integrity of the cable to safety devices [2] (e.g., electromagnets on fire doors, ensuring they can close during a fire)
- **input modules:** receive feedback signals (e.g., after the control panel sends a signal to close a fire damper, the input module confirms it has physically reached the closed position)

2.3. Smoke dynamics and smoke and heat control systems (SHCS)

Smoke spreads significantly faster than flames, filling evacuation routes with toxic gases and reducing visibility, which severely impacts human evacuation behaviour [1]. Following detector activation, the system activates the SHCS via modules in accordance with relevant standards such as HRN EN 12101-1 [3] and HRN EN 12101-3 [4].

2.3.1. Smoke Curtains and Smoke Zoning

In large atriums or shopping centres, smoke spreads horizontally under the ceiling. Fire alarm modules lower the smoke curtains to limit horizontal smoke movement and help maintain smoke reservoirs; the alarm signal then initiates the programmed smoke-control sequence. These curtains do not stop fire but prevent the smoke from cooling and descending to the floor, keeping it in upper "smoke reservoirs" where fans can easily extract it [3].

The smoke extraction system operates in two ways:

- **natural smoke extraction**: automatic opening of smoke domes and specialized windows on the roof or upper parts of the building
- **forced smoke extraction** [4]: activation of fans that pull smoke and hot air out of the building.

By opening domes, smoke and heat exit naturally upwards. Without effective smoke extraction, smoke would spread rapidly throughout the building, significantly hindering escape. Therefore, the automatic opening of smoke domes and windows, together with smoke curtains, represents one of the key fire safety and occupational health and safety measures.

2.4. Integration with HVAC systems

Heating, Ventilation, and Air Conditioning (HVAC) systems provide a comfortable microclimate normally but can become "highways" for smoke transport between floors during a fire.

2.4.1. Shut down of ventilation units

One of the system's first automated actions is to shut down all standard air handling units (AHUs) used for comfort (daily heating, cooling and ventilation). Relay modules interrupt the power to frequency converters or motors. This prevents the ventilation from supplying fresh oxygen to the fire zone and spreading smoke throughout the building.

2.4.2. Fire damper management

Fire dampers are mechanical barriers within ducts. They must have fire resistance ratings defined in accordance with standard HRN EN 13501-3 (e.g., EI 90 or EI 120 minutes) [5] and product specification HRN EN 15650 [6]. Upon fire detection, the module releases an electromagnet or triggers a motor to close the damper. Where specified by the selected damper and actuator design, these dampers operate on a "fail-safe" principle: if power is lost or a cable burns, they close automatically via mechanical spring return action.

2.5. Safety in Ex-zones

2.5.1. Application of Zener barriers

In industrial plants where flammable gases, vapors or explosive dust are present, every electrical device represents a potential hazard. Even a minor electrical signal or spark can trigger an explosion that would endanger workers' lives, destroy equipment and lead to a major workplace accident. In these hazardous zones (known as Ex-zones), it is not permitted to use standard fire detector wiring and connections typically found in ordinary premises.

In these high-risk areas, the fire detection system must meet strict safety requirements. Instead of conventional connection methods, the concept of intrinsically safe protection is applied. Intrinsic safety is assessed in accordance with applicable standards, where the appropriate protection method depends on the specific hazardous-area classification and system design.

A Zener barrier operates on the principle of limiting electrical energy using specialized diodes and resistors. When a normal signal passes toward the detector, the barrier allows the necessary voltage and current for the detector to function correctly. However, if a fault occurs (e.g., excessive voltage from the control panel), the Zener diodes instantly "break down" and divert the excess energy to the ground, while resistors limit the current to a safe level - one that is insufficient to cause ignition of an explosive gas or dust atmosphere. In this way, the energy reaching the Ex-zone always remains below the ignition threshold in accordance with standards such as HRN EN IEC 60079-11 [7] and HRN EN 60079-25 [8].

This measure is of utmost importance for occupational safety. Workers in Ex-zones (e.g., in the chemical industry, refineries or dust silos) are often exposed to high risks. Zener barriers allow fire detectors to be used safely even in the most dangerous parts of a plant without increasing the risk of explosion. This provides workers with reliable protection - the system can detect a fire in a timely manner without becoming the cause of a catastrophe itself.

Without this protection, any fire in an Ex-zone could rapidly escalate into a devastating explosion. This is why the use of Zener barriers and the concept of safety is mandatory in all areas where an explosive atmosphere may be present. By implementing these measures, an integrated fire detection system simultaneously protects workers' lives and prevents the spread of fire in the most high-risk sections of an industrial facility.

2.5.2. Application of short-circuit isolators

To achieve a high level of reliability across loop circuits, short-circuit isolators are used in accordance with standards such as HRN EN 54-17 [9]. These components constantly monitor electrical parameters within the fire detector loop. When cable damage or a short circuit occurs due to fire, the isolator reacts within a fraction of a second to automatically disconnect the faulty section, while the remaining loop continues to operate without interruption. This prevents a single localized fault from disabling the protection system for the entire building.

Thanks to this operation, detectors in other zones remain functional to detect danger and initiate alarm functions. Simultaneously, the fire alarm control panel receives precise information regarding the fault location, speeding up technical intervention.

2.5.3. Difference between Zener barriers and short-circuit isolators

Although both components enhance overall system reliability, they serve distinct technical functions:

- Zener (or galvanic) barrier: A device designed for intrinsic safety in Ex-zones, limiting electrical energy (voltage and current) below ignition thresholds to prevent sparks in explosive atmospheres.
- Short-circuit isolator: A loop protection component focused on maintaining network communication integrity; it isolates short-circuited cable segments without modifying operating energy for Ex-zone applications.

In practical terms, Zener barriers prevent electrical equipment from causing an explosion in hazardous zones, whereas short-circuit isolators ensure loop operation continues even when fire damages part of the wiring.

2.6. Vertical transport and evacuation safety

Human behaviour during a fire depends on clear instructions and unobstructed paths.

2.6.1. Elevators and escalators

Elevators must never be used for evacuation (except for specialized firefighting elevators). Automation ensures the following:

Elevators: The elevator ignores all external and internal calls, proceeds to the evacuation floor (usually the ground floor), opens its doors and remains locked out.

Escalators: Modules stop the operation of escalators. This shutdown must be controlled to avoid sudden jerks that could cause people on them to fall.

2.6.2. Integration with access control and public address systems

In access-controlled facilities, the fire detection system transmits signals via modules to release electromagnetic locks along designated evacuation routes, unlatching fire and sliding doors for unobstructed egress.

Simultaneously, normal public address broadcasts are overridden by the Voice Alarm (VA) system. In accordance with HRN EN 54-16 [10], these systems provide pre-recorded spoken emergency instructions designed to improve message clarity during evacuation compared to conventional sounders alone. Clear verbal guidance helps occupants evacuate in an orderly manner without unnecessary confusion or panic.

2.7. Maintenance, testing and legal regulations

A fire detection system is only useful if it is functional. According to national legislation [11] [12] and applicable standards, fire alarm systems must undergo regular inspection and maintenance to ensure operational readiness.

Annual functional testing

Once a year, periodic functional testing is conducted by a legal entity authorized by the competent authorities (e.g., the Ministry of the Interior). The scope of this annual inspection includes verifying the coordinated operation of the entire system:

- testing the operation of all detectors (smoke, heat, gas and manual call points),
- inspecting input/output and relay modules,
- verifying executive control functions (smoke extraction, smoke curtains, fire dampers, ventilation shutdown, door release, elevator recall, voice alarms),
- checking main and secondary power supplies (batteries),
- simulating false and real alarms to verify the correct system response and
- inspecting cables, connections and protective elements in Ex-zones.

Following successful verification, the authorized entity issues a compliance certificate as prescribed by national regulations.

Twice-yearly functional check and preventive maintenance

Twice a year (every 6 months), regular preventive maintenance is performed. This includes:

- cleaning and calibration of detectors,
- checking control module states,
- testing battery backup autonomy,
- verifying system software integrity and
- carrying out routine repairs or replacements of worn components.

Both the annual testing and the twice-yearly preventive maintenance must be recorded in the system logbook by the facility owner or designated maintenance personnel to demonstrate regulatory compliance.

3. CONCLUSION

Automation of critical safety functions - from smoke extraction to door unlocking - can support timely and coordinated evacuation during a fire emergency.

An integrated fire detection system activated via control modules represents a modern approach to fire protection in buildings. From fire detection, smoke extraction, and compartmentation to elevator safety, clear voice instructions, and exit unlocking - system components work together automatically. When appropriately designed, integrated, tested, and maintained, such integrated systems can significantly improve protection for human life and health, reducing the risk of injury, suffocation, panic, and secondary accidents in accordance with occupational safety and fire protection principles.

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Original scientific paper

DEVELOPMENT AND EXPERIMENTAL EVALUATION OF A METHODOLOGY FOR INTEGRATING CFD SIMULATIONS INTO VIRTUAL REALITY FOR FIREFIGHTING TRAINING IN SHIP ENGINE ROOMS

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Abstract: *Ship engine room fires represent one of the most challenging emergency scenarios in maritime transport. This study presents a reproducible methodology for integrating Computational Fluid Dynamics (CFD) fire simulations into an immersive Virtual Reality (VR) training environment. SmartFire simulation results were converted into volumetric datasets and integrated into Unreal Engine using an OpenVDB-based workflow. The developed system was evaluated by 22 operational firefighters through a comparison of conventional graphical and CFD-based smoke visualizations. Although no statistically significant differences were observed, the CFD-based approach consistently achieved higher mean evaluation scores. The proposed methodology provides a practical framework for developing more realistic physics-based VR firefighting training systems.*

Keywords: *Computational Fluid Dynamics; Virtual Reality; firefighting training; ship engine room; fire simulation*

1. INTRODUCTION

Ship engine room fires are among the most severe emergencies in maritime operations because of confined compartments, the presence of combustible liquids, and complex ventilation conditions that accelerate fire growth and smoke propagation, [1–3]. Such incidents pose a serious threat to

crew safety, vessel integrity, and environmental protection. Consequently, international maritime regulations require seafarers to receive regular firefighting training to ensure an effective response during emergency situations, [3].

Traditional firefighting training primarily relies on physical training facilities and live-fire exercises. However, reproducing realistic engine room fire scenarios is often restricted by safety requirements, high operational costs, limited accessibility, and environmental considerations, [4, 5]. These limitations have encouraged the development of computer-based training methods capable of providing safe, repeatable, and cost-effective learning environments.

Computational Fluid Dynamics (CFD) has become an established approach for simulating fire development, smoke propagation, heat transfer, and ventilation effects in enclosed ship compartments, [6–11]. At the same time, Virtual Reality (VR) enables immersive and interactive training environments in which users can practice emergency response procedures without exposure to real hazards, [12–15]. The combination of these technologies offers the possibility of creating physically realistic training scenarios while maintaining the flexibility and safety advantages of virtual simulation.

Although previous studies have investigated VR-based firefighter training and several have explored the integration of fire simulations into virtual environments, [19–25], relatively few have presented a complete and reproducible methodology for transferring volumetric CFD fire simulation results into an interactive VR environment. Furthermore, only a limited number of studies have evaluated such systems using operational firefighters under conditions representative of maritime firefighting training. This gap motivates the research presented in this paper.

The objective of this study was to develop and experimentally evaluate a reproducible methodology for integrating CFD fire simulation results into a VR environment intended for firefighting training in ship engine rooms. The proposed workflow enables the conversion of SmartFire simulation outputs into volumetric datasets suitable for visualization in Unreal Engine while preserving the spatial and temporal characteristics of the simulated fire. The developed methodology was evaluated through a comparative user study involving operational firefighters who assessed a CFD-based smoke visualization against a conventional graphical approach. The primary scientific contribution of this work is a reproducible CFD–VR integration methodology accompanied by its experimental validation in a professional firefighting training context.

2. METHODOLOGY

2.1. Ship Engine Room Model

The study was conducted using a three-dimensional model of a Ro-Ro ship engine room measuring 19.6 × 16.1 × 9.0 m and consisting of two deck levels. The model included the main propulsion engines, auxiliary diesel generators, pumps, piping systems, cooling equipment, and other machinery representative of a typical merchant vessel engine room. The geometry was developed from technical drawings and refined through consultation with experienced chief engineers to ensure realistic equipment arrangement and spatial configuration.

To reduce computational cost, auxiliary spaces not directly affecting fire development were excluded, while selected structural components were geometrically simplified without altering the overall airflow characteristics. The same geometric model was used for both CFD simulations and the VR environment to ensure complete spatial consistency throughout the workflow (Fig. 1).

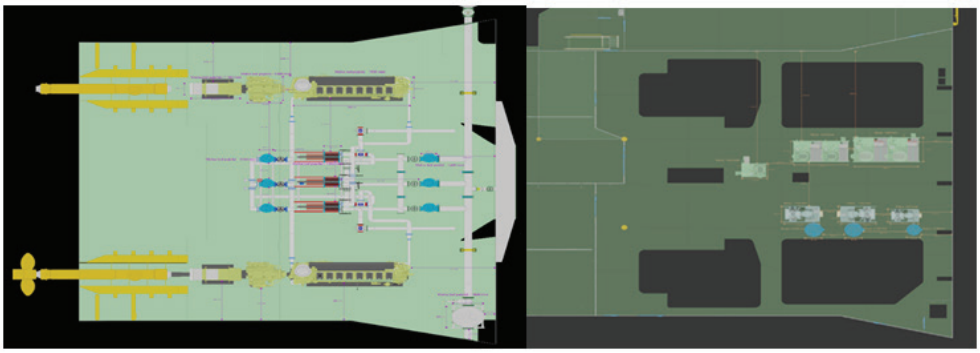


Figure 1. Three-dimensional model of the ship engine room used for CFD fire simulations and VR implementation.

2.2. CFD Fire Simulation

Fire simulations were performed using SmartFire software, a CFD package specifically developed for modelling compartment fires. The numerical model employed the Large Eddy Simulation (LES) approach to predict fire development, smoke propagation, heat transfer, and ventilation-induced airflow.

The computational domain was discretized using approximately 607,600 control volumes, with the final mesh selected following a mesh independence study performed over a range of approximately 200,000 to 2,000,000 cells. All solid boundaries were treated as adiabatic no-slip walls, while the initial air temperature was set to 25 °C.

The fire scenario represented a realistic engine room fire involving combustible liquid ignition. Simulation outputs included three-dimensional distributions of temperature, smoke concentration, velocity, and other relevant fire parameters required for subsequent visualization within the VR environment.

2.3. CFD–VR Data Integration

The proposed methodology converts SmartFire simulation outputs into volumetric datasets compatible with OpenVDB, enabling efficient storage and visualization of transient smoke fields. A custom-developed C++ application was implemented to automate the conversion process and preserve the spatial and temporal characteristics of the CFD solution.

The resulting volumetric datasets were imported into Unreal Engine 5, where they were integrated into an interactive VR engine room environment. This workflow enabled physics-based visualization of smoke development while maintaining synchronization with the original CFD simulation.

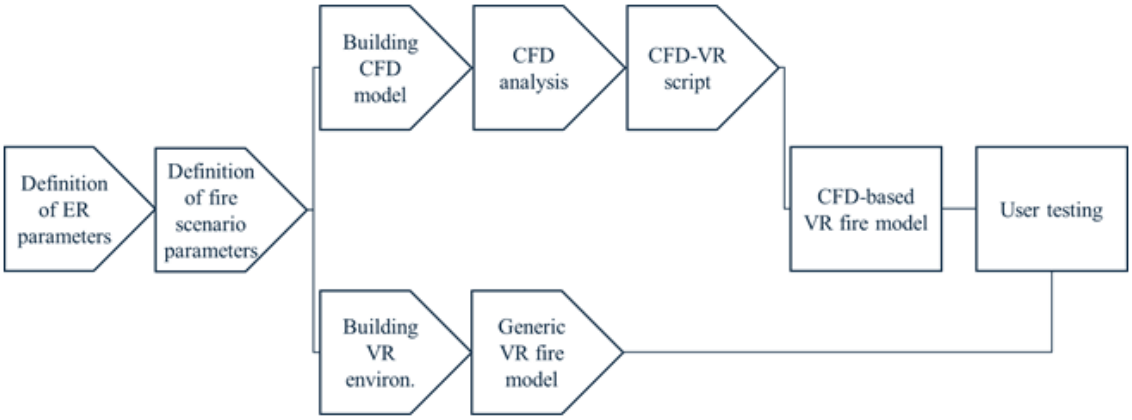


Figure 2. Workflow for integrating CFD fire simulation results into the virtual reality environment.

2.4. Experimental Evaluation

The developed VR system was evaluated by 22 firefighters with operational firefighting experience. Each participant completed two virtual scenarios representing identical fire conditions:

- Conventional graphical smoke visualization;
- CFD-based volumetric smoke visualization.

To minimize the potential influence of presentation order, the sequence of the two visualization scenarios was alternated among participants.

2.5. Questionnaire and Statistical Analysis

Following each VR session, participants completed a structured questionnaire assessing:

- Visual realism,
- Smoke behaviour,
- Influence of ventilation,
- Spatial perception,
- Overall realism.

Responses were recorded using a six-point Likert scale. Differences between the two visualization approaches were analysed using the Wilcoxon signed-rank test because the collected data were ordinal and paired. Statistical significance was established at $p < 0.05$.

3. RESULTS

3.1. CFD Fire Simulation

The CFD simulation successfully reproduced the development of the engine room fire, including smoke propagation, temperature distribution, and airflow patterns under the selected ventilation

conditions. Smoke initially accumulated beneath the ceiling before spreading through the upper compartment and gradually descending as the fire progressed. Ventilation significantly influenced smoke movement, producing locally increased flow velocities and non-uniform smoke distribution throughout the engine room.

The simulation generated time-dependent volumetric datasets describing smoke concentration, temperature, and flow characteristics, which served as the basis for subsequent VR visualization.

3.2. CFD–VR Integration

The proposed workflow enabled successful conversion of SmartFire simulation outputs into OpenVDB volumetric datasets compatible with Unreal Engine 5. The developed conversion tool preserved both the spatial distribution and temporal evolution of smoke, allowing direct visualization of transient CFD results within the VR environment.

Compared with the conventional particle-based smoke effects available in Unreal Engine, the CFD-based visualization reproduced physically consistent smoke movement governed by the simulated fire dynamics and ventilation conditions.



Figure 3. Comparison of conventional graphical smoke visualization (left) and CFD-based volumetric smoke visualization (right) in the virtual ship engine room.

3.3. User Evaluation

Twenty-two operational firefighters completed the comparative evaluation of both visualization approaches. Across most questionnaire items, the CFD-based visualization achieved higher mean scores than the conventional graphical visualization. The largest differences were observed in the perceived realism of smoke behaviour, the influence of ventilation on smoke movement, and the overall realism of the virtual environment.

Although the CFD-based approach consistently received higher average ratings, the Wilcoxon signed-rank test indicated that none of the observed differences reached the predefined level of statistical significance ($p < 0.05$).

The results therefore suggest a consistent user preference for the CFD-based visualization while indicating that additional studies involving larger participant samples are required to confirm statistically significant differences. Figure 4 presents the comparative evaluation results for all participants and for the subgroup of experienced firefighters.

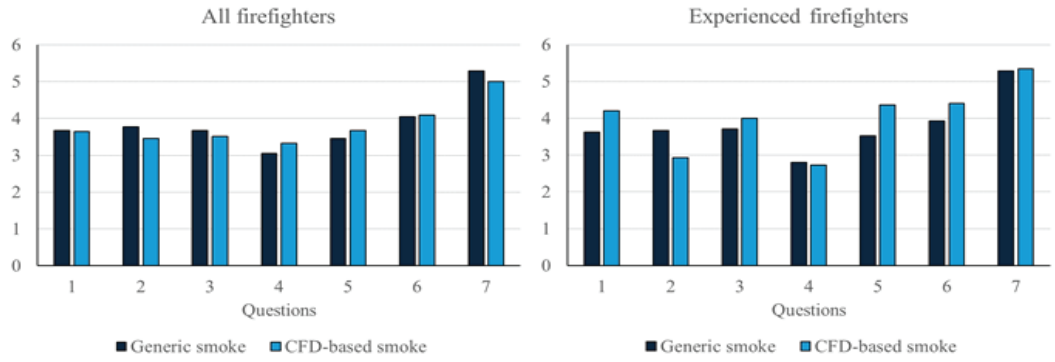


Figure 4. Comparison of participants' evaluation scores for the conventional and CFD-based smoke visualizations.

4. DISCUSSION

The present study developed and experimentally evaluated a reproducible methodology for integrating CFD fire simulation results into an immersive VR environment for ship engine room firefighting training. The proposed workflow successfully enabled the transfer of transient volumetric CFD data into Unreal Engine while preserving the spatial and temporal characteristics of smoke propagation. This approach provides a practical framework for incorporating physics-based fire behaviour into VR training systems.

The user evaluation demonstrated that operational firefighters consistently assigned higher average ratings to the CFD-based visualization than to the conventional graphical smoke representation. The greatest differences were observed for smoke realism, ventilation effects, and overall environmental realism. Although these differences were not statistically significant, the consistent trend suggests that physically based smoke visualization is perceived more favourably by experienced end users.

Previous studies have demonstrated the educational potential of VR for firefighter training, [19, 20, 23, 24]. Other researchers have investigated the integration of fire dynamics into virtual environments, [21, 22]. However, relatively few studies have presented a complete methodology for transferring CFD simulation data into VR while validating the resulting system with operational firefighters. The present study contributes to this field by combining a reproducible CFD–VR workflow with experimental user evaluation, thereby extending previous research beyond software development or visualization alone, [25].

The proposed methodology is not limited to maritime firefighting training. Because it is based on transferable volumetric CFD data, it can be adapted to other safety-critical applications, including industrial facilities, offshore platforms, tunnels, energy infrastructure, and emergency response training environments where realistic live-fire exercises are difficult or unsafe to perform.

Several limitations should be acknowledged. The evaluation involved a relatively small sample of operational firefighters and considered only one engine room fire scenario. In addition, the assessment relied on subjective user perception rather than objective performance indicators such

as response time, decision-making accuracy, or task completion efficiency. Future research should include larger participant groups, multiple fire scenarios, and objective performance measures to further validate the proposed methodology.

5. CONCLUSION

This study presented and experimentally evaluated a reproducible methodology for integrating Computational Fluid Dynamics (CFD) fire simulation results into an immersive Virtual Reality (VR) environment for firefighting training in ship engine rooms. The proposed workflow enables the conversion of SmartFire simulation outputs into volumetric OpenVDB datasets that can be visualized in Unreal Engine while preserving the spatial and temporal characteristics of smoke propagation.

The developed methodology was evaluated by 22 operational firefighters through a comparative assessment of a CFD-based smoke visualization and a conventional graphical approach. Although statistically significant differences were not observed, the CFD-based visualization consistently received higher average ratings across most evaluation criteria, indicating its potential to enhance the perceived realism of VR-based firefighting training.

The principal contribution of this research is not the development of a new VR application, but the establishment and experimental validation of a reproducible CFD–VR integration methodology. The proposed approach provides a foundation for future physics-based training systems in maritime education and can be extended to other safety-critical industrial environments where realistic emergency training is required.

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Professional paper

ELECTRICAL ENGINEERING ASPECTS OF THE DESIGN, INSTALLATION AND TESTING OF FIRE DETECTION SYSTEMS

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Abstract: *The paper will present the basic principle of operation of a fire alarm system, key elements that ensure timely fire detection and reliable system functioning, as well as requirements related to the design of installations, selection of appropriate equipment and proper connection of system elements. The technical circumstances and normative standards that must be fulfilled during system installation are also examined. The steps for verifying and validating the system's accuracy following installation are explained. Finally, a report on the professional examination and testing of the fire alarm system in use will be included in this article.*

Keywords: *fire alarm system, analogue addressable system, fire detectors, zoning, testing*

1. INTRODUCTION

Fire protection is a fundamental safety requirement for buildings, and fire alarm systems represent the first technical level of recognizing a hazardous event. Their purpose is to detect smoke, heat, combustion gases or a manually activated alarm at the earliest possible stage and to transmit this information to the fire alarm control panel. The control panel then initiates local and remote alarm functions, activates sounders and visual indicators, and can control other safety-related installations such as ventilation shutdown, fire doors, smoke extraction or extinguishing systems.

The starting point of this paper is that system reliability cannot be evaluated only through the quality of individual components. A certified detector may still perform poorly if it is selected without regard to room use, installed in an unfavourable position, connected to an inadequately designed circuit or left without regular testing. For that reason, the paper focuses on the connection between design, installation and testing, with emphasis on the electrical engineering decisions that influence timely and unambiguous fire detection.

2. DESIGN AND REGULATORY FRAMEWORK

The design of a fire alarm system must be coordinated with the general fire protection concept of the building, the fire protection study, project documentation and applicable technical rules. The fire protection study defines fire compartments, occupancy, evacuation requirements, risk level and necessary active and passive fire protection measures. Based on these inputs, the designer defines the protected area, type and number of detectors, zoning logic, signalisation, control panel location, power supply, cable routes and alarm scenarios.

In practice, it is important to distinguish formal compliance from functional reliability. A system may be installed and documented, but still be difficult to use during an emergency if zones are too large, if address descriptions are unclear or if the alarm scenario is not coordinated with the building's evacuation and intervention plan. Therefore, fire alarm documentation should include a technical description, detector layout drawings, circuit and loop diagrams, power supply calculations, alarm plan, operating instructions and maintenance requirements [1], [2], [3].

3. SELECTION OF SYSTEM CONCEPT

One of the most important design decisions is the choice between a conventional and an analogue addressable system. Conventional systems are suitable for smaller and simpler buildings because the alarm is indicated at the zone level. Such systems are easier to design and install, but the exact activated detector must be verified by inspecting the zone on site. In larger and more complex buildings, this can prolong the time needed for localization and intervention.

Analogue addressable systems are based on a loop in which each detector, manual call point or module has a unique address. The control panel cyclically polls the connected devices, receives analogue values and distinguishes normal condition, pre-alarm, alarm and fault. This enables precise location information, continuous supervision, short-circuit isolation and more complex programmed control functions [4], [5], [6], [7].

Table 1: Comparison of conventional and analogue addressable fire alarm systems

Criterion	Conventional system	Analogue addressable system
Alarm location	Alarm is shown at zone level; the exact detector must be checked on site	The control panel shows the address and description of the activated device
Wiring	Several circuits are commonly required for zones and functions	A two-wire loop carries both supply and data for different field devices
Fault supervision	Circuit interruption and short circuit are supervised mainly at circuit level	Devices and loops are continuously supervised; a faulty section can be isolated
Typical use	Smaller buildings with simple geometry and fewer zones	Larger and technically complex buildings with several fire compartments
Intervention	Localization is slower because the whole zone must be checked	Localization is faster and better supports emergency response

4. LOOP DESIGN, DETECTOR PLACEMENT AND ZONING

In an analogue addressable system, a loop is a two-wire circuit that starts from the fire alarm control panel, connects addressable devices and returns to the panel. The same wiring path carries operating voltage and communication data. Loop design therefore includes the number of devices, cable length, voltage drop, current consumption and behaviour in fault conditions. The designer must ensure sufficient voltage at the most unfavourable point of the loop in both normal and alarm conditions.

Detector placement depends on room purpose, ceiling height and geometry, air movement, suspended ceilings, obstacles, dust, steam and technological processes. Optical smoke detectors are suitable for clean spaces where smoke is expected in an early phase. Heat detectors are used where steam, dust or process-related smoke could cause unwanted alarms. Multi-sensor detectors combine smoke, heat and carbon monoxide measurements, which can reduce false alarms when the selected operating mode matches the room conditions [5], [8]. Manual call points are installed along escape routes and near exits so that occupants can activate the alarm if they notice a fire.

Zoning is not only an administrative division of the system. Zones should follow fire compartments, floors, building wings or functional units so that an alarm display immediately provides useful information for verification and intervention. A zone that is too large makes localization difficult, while excessive fragmentation can make operation and documentation unnecessarily complex. Good zoning links the technical display at the control panel with the actual organization of evacuation and firefighting response.

5. INSTALLATION, PROGRAMMING AND POWER SUPPLY

Installation transfers the designed solution into the physical building. The contractor must follow the approved design, manufacturer instructions and technical requirements for cable type, routing, mechanical protection, device mounting and connection. The fire alarm control panel should be installed in a dry, accessible and supervised location. The plan of the system, alarm plan, maintenance log and operating instructions should be available near the panel to support users, maintenance personnel and emergency services.

For addressable systems, physical installation is only the first step. Each field device must receive a unique address, and the control panel must be programmed with zone assignments, text descriptions, alarm thresholds and output functions. The selected operating mode of multi-sensor detectors is particularly important. In offices and corridors, smoke detection may be dominant, while technical spaces with dust or steam may require a different balance between heat, smoke and carbon monoxide channels.

Power supply is another essential reliability factor. A fire alarm system must have a primary power source and a standby battery supply. The transfer to standby supply must not interrupt supervision and alarm operation. Battery capacity must be selected according to the required standby time, alarm load and manufacturer specifications. During testing, both the mains supply and the standby source have to be verified because loss of supply can make an otherwise correctly designed detection system ineffective.

6. TESTING AND VERIFICATION

Testing proves whether the installed system corresponds to the design and whether all functions operate as intended. Initial testing before commissioning includes inspection of project documentation, comparison of installed and designed conditions, review of certificates and usability documents, testing of detectors, manual call points, sounders, visual indicators, control outputs, power supply and fault signals. The results are recorded in a test report, and if the system is satisfactory, a certificate of correctness is issued [3].

Periodic testing is necessary because the conditions in a building change over time. Room use may change, detectors may become contaminated, batteries lose capacity, cable routes may be damaged and users may modify evacuation procedures. Periodic testing therefore verifies not only individual detectors, but the complete functional chain: alarm detection, transmission, fault indication, standby power, sound pressure, visual indication, activation of connected systems and maintenance documentation.

Table 2: Reliability checkpoints through the life cycle of a fire alarm system

Phase	Key engineering decision	Evidence or result
Design	Define protected area, detector type, zones, loops, voltage drop and alarm scenario	Project documentation, calculations, drawings and alarm plan
Installation	Install equipment according to design, standards and manufacturer instructions	Correct addressing, mounting, wiring supervision and power supply
Commissioning	Verify the installed system against the approved design	Test report and certificate of correctness
Periodic testing	Regularly verify all devices, power supply and connected functions	Updated maintenance log, reports and corrective actions

7. DISCUSSION

The analysis shows that the greatest risk for fire alarm reliability is a fragmented approach. If design is reduced to placing detectors, installation to connecting devices and testing to a formal document, the system can satisfy only part of its purpose. Reliable fire detection is achieved when design assumptions are preserved during installation and later confirmed through testing. This is especially important for addressable systems, whose technical advantages depend on clear zone logic, correct addressing and understandable panel descriptions.

Analogue addressable systems offer better diagnostic information and more flexible alarm scenarios than conventional systems. However, the benefit is lost if documentation is poor or if users cannot interpret alarms and faults. For that reason, reliability should be treated as a life-cycle property rather than a single technical feature. The system has to remain understandable, testable and maintainable throughout its operating life.

8. CONCLUSION

Fire alarm systems are a key element of active fire protection because they enable early detection, alarm transmission and activation of protective functions. Their reliability depends on system concept selection, spatial analysis, loop and circuit design, detector placement, zoning, control panel programming, power supply and regular testing. Analogue addressable systems provide significant advantages in localization, supervision and integration, but only if they are designed, installed and tested as a coherent whole.

A reliable fire alarm system should therefore be understood as the result of coordinated work between designer, installer, testing body and building user. Such an approach reduces false alarms, improves alarm localization and supports faster emergency response, thereby increasing the protection of people, property and the environment.

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Original scientific paper

APPLICATION OF THERMAL CAMERAS IN FIRE FIGHTING: FREQUENCY, EFFECTIVENESS AND USER PERCEPTION

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Abstract: *The topic of this paper is research on the use of thermal cameras in firefighting, with an emphasis on their frequency of use, effectiveness, and user perception. Thermal cameras are an important tool in modern firefighting because they enable faster and more precise identification of fire sources, search for people in conditions of reduced visibility, and detection of hidden hot spots. The aim of the research was to examine firefighters' experiences and attitudes toward the use of thermal cameras, using a specially designed questionnaire administered to a population of 62 respondents. The results obtained showed that thermal cameras are widely used in fire departments, but their availability still depends on material conditions and financial capabilities. Also, it has been shown that experience and confidence in handling cameras increase with additional training, practical exercises, and fieldwork. The study's conclusions confirm all four hypotheses and emphasize the importance of systematic investment in equipment and firefighter education.*

Keywords: *thermal cameras, firefighting, efficiency, safety, user perception*

1. INTRODUCTION

Technological advances over the past few decades have brought significant improvements in safety and the protection of people and property. One such innovation is thermal imaging cameras (TIC), which were initially intended exclusively for military and specialized technical applications, but are now widely used in firefighting and other emergency services. They enable the visualization of temperature differences within a space and thus provide operational teams with the ability to detect hot spots, locate people in conditions of reduced visibility, and make more precise decisions in stressful and high-risk situations. Their application is not limited to firefighters directly involved in fire interventions; they are also used at command levels, such as by operations leaders and incident commanders, where they contribute to better situational assessment and more effective operational management.

The topic and objective of this research were to analyze the frequency of thermal camera use, their effectiveness under various intervention conditions, and users' perceptions, with an emphasis on the experiences and attitudes of operational firefighters. In this way, the study sought to determine not only the prevalence of this technology in fire departments but also the actual experiences that demonstrate the extent to which thermal cameras contribute to the safety, speed, and quality of interventions.

Most of the literature in the Croatian context is not truly empirical; rather, it consists of short review papers and editorial articles. When research that strictly includes firefighters as respondents (surveys, experiments, field measurements) is searched for, the picture becomes much narrower and is mostly international. In the study [1] conducted in the USA, a survey was conducted among 80 fire departments (67 responses), identifying perceived benefits (safety, effectiveness), the use of TICs in 26.8% of departments, and finances as the main barrier to greater use. In the NIST report [2], research was conducted among American firefighters as a controlled experiment in which respondents were required to perform recognition based on TIC images. Therefore, this was a user experience study that found that performance depends on image contrast, resolution, and noise. In study [3], research was conducted among departments, and an evaluation instrument was developed. Based on user perception and experience (indirect satisfaction), competencies, training, and operational use were assessed. In the market survey [4], a structured user evaluation was conducted without a formal “satisfaction scale,” and the article itself lacks academic weight. The results showed that TICs increase the speed of locating hot spots and victims and improve safety and situational awareness. Several more recent papers can also be mentioned, such as [5], which addresses the use of TICs in actual firefighting interventions and their impact on operational effectiveness; [6], which analyzes barriers to the introduction of TICs into fire departments; and [7], which analyzes firefighters' occupational safety through the introduction of new technologies into firefighting. Therefore, no published peer-reviewed papers have been recorded in Croatia that analyze the frequency and effectiveness of TIC use based on firefighters' experiences and perceptions as users.

2. METHODOLOGY

In accordance with the research objective, theoretical research was first conducted, including an analysis of the specific characteristics of TICs as a technological solution [8], their applicability in firefighting, and market conditions for procurement [1]. Some available sources on previous relevant research conducted on the examination and assessment of experiences with the field use of TICs, several of which were already mentioned in the Introduction, were also analyzed. Based on insights from the theoretical research and the authors' own practical experience, four hypotheses were formulated: H1—Thermal cameras are widely used in fire departments [9]; H2—Firefighters who use thermal cameras identify the source of a fire more quickly and accurately [5]; H3—Firefighters' experience in using thermal cameras improves with higher levels of training and the practical use of equipment [7]; H4—The reason for not owning thermal cameras is mainly a lack of material resources [6].

The research was conducted using an electronic form created on Google Forms. Participants were required to answer either 18 or 12 questions. The form consists of 23 questions; however, question 7 is selective, and the respondent's answer determines which subsequent group of questions they proceed to: Group A, consisting of 11 questions, or Group B, consisting of 5 questions.

The first section of the questionnaire related to sociodemographic data on the sample population and basic information about firefighting work. The next section examined the use of TICs, as well as experiences and attitudes. The final section examined participants from departments without a TIC camera, along with their attitudes and work experience. A 5-point Likert scale was used in six questions.

The research was conducted electronically from May to August 2025. The target population consisted of firefighters from throughout the Republic of Croatia. The forms were distributed electronically, primarily via email and WhatsApp. The analysis of the results was performed using Microsoft Excel, and the results presented here were analyzed from tables and various types of charts. Participants took part in the research voluntarily and anonymously.

3. RESULTS

The research participants were firefighters from throughout the Republic of Croatia. A total of 62 participants completed the survey.

Basic sociodemographic data were covered by the first six questions of the questionnaire. The study included 56 male respondents (90%) and 6 female respondents (10%). In the further analysis of the results, the generic use of the masculine form will be used with implied gender neutrality.

The largest number of respondents was in the 21–30 age group, with 19 respondents (31%), followed by the 31–40 age group, with 16 respondents (26%). There were 14 respondents (23%) aged 41–50, and 12 respondents (19%) were older than 50. The smallest number of participants was in the group aged 20 or younger, with 1 participant (2%).

The county with the largest number of respondents was Brodsko-Posavska County, with 29 respondents (47% of the total). The next county by number of respondents was Požeško-Slavonska County, with 8 respondents (13%). Seven respondents (11%) each work in Osječko-Baranjska County and Primorsko-Goranska County. Two respondents each (3%) work in Karlovačka County and Vukovarsko-Srijemska County. In Virovitičko-Podravska, Varaždinska, Šibensko-Kninska, Međimurska, Sisačko-Moslavačka, and Zagrebačka counties, as well as the City of Zagreb, there was 1 respondent each (2%).

Firefighters in the Republic of Croatia can serve in various institutions and associations. Most commonly, these are public and volunteer fire departments, as reflected in the research results. The largest number of respondents work in public fire departments, with 44 respondents (71%). A large proportion of respondents also work in volunteer fire departments, with 15 respondents (24%). The option “Other” was selected by 3 respondents (5%).

Of the 62 respondents, the largest number had 10 to 20 years of experience, totaling 22 respondents (35%). Thirteen respondents (21%) had 5 to 10 years of work experience, the same number as in the 20 to 30 years of work experience category. Eight respondents (13%) reported more than 30 years of experience. The smallest group had less than 5 years of work experience, with 6 respondents (10%).

Education for firefighting activities is based on the principle of lifelong learning. Education for firefighting activities includes acquiring qualifications and undertaking non-formal education.

Qualification acquisition is carried out by the State Firefighting School in cooperation with the Croatian Firefighting Association, in accordance with the statute and the law governing adult education. Of the 62 respondents, a total of 45 (73%) had acquired a qualification in the field of firefighting. Seventeen respondents (27%) did not have such a qualification, and none were in the process of obtaining one.

As already stated in the Methodology, in this rating section of the questionnaire, the question "7. Does your department have a thermal camera?" served as a filter: respondents who answered affirmatively continued with questions about experience and frequency of use, while those who answered negatively were redirected to questions about reasons for not owning one and an assessment of the importance of this equipment. Of the 62 respondents, 51 (82%) answered affirmatively to this question, while 11 (18%) answered negatively.

To the question "1a. How often do you use a thermal camera during interventions?", the largest number of respondents, a total of 20 (39%) answered "Almost at every intervention." Fourteen respondents (27%) answered "More than 10 times per year." Thirteen respondents (25%) reported using a thermal camera 5–10 times per year, while 4 respondents (8%) reported using it fewer than 5 times per year. Of the 20 respondents who reported a very high frequency of thermal camera use during interventions, 17 (85%) work in public fire departments. Two respondents work in volunteer fire departments, and one in other institutions.

The question "2a. How would you rate your skill in handling a thermal camera?" was designed as a 1-5 scale, where 1 indicates "very insecure", and 5 indicates "excellent." It provides a self-assessment of firefighters' level of competence. The largest number of respondents, 21 (41%), rated themselves 4. In addition, 19 respondents (37%) rated themselves 5, "excellent." Seven respondents (14%) rated themselves with the middle score of 3, 4 respondents (8%) gave themselves a score of 2, while no one considered their handling skill to be 1, or "very insecure."

The question "3a. How confident do you feel using a thermal camera in stressful situations?" focused on the psychological dimension of equipment use, since actual intervention conditions often involve high levels of stress, limited visibility, and time pressure. The largest number of respondents, 27 (53%), answered with the highest score, "5—completely confident." This was followed by score 4, selected by 20 respondents (39%). Three respondents (6%) selected the middle value on the scale (3), and only 1 respondent (2%) selected score 2. None of the respondents felt completely insecure.

The question "4a. How would you assess your understanding of the interpretation of the thermal camera display (colors, temperatures, patterns)?" represents a self-assessment of understanding the interpretation of the thermal camera display. The answers were also offered on a scale from "1—I understand very poorly" to "5—I fully understand." The largest number of respondents, 23 (45%), stated that they fully understood. Furthermore, 20 respondents (40%) rated themselves at 4. Six respondents (12%) rated themselves with the middle score of 3. Only 2 respondents (4%) rated themselves 2, while no one reported understanding very poorly.

For the question "5a. In which situations do you consider a thermal camera especially useful?", respondents were offered nine response options, as well as an additional option in which they could add their own answer. The following responses were offered: locating the fire source; locating hidden fires (e.g., in walls, ceilings); locating people in smoke-filled spaces; locating injured persons in open areas; assessing structural stability (detecting overheated elements); monitoring fire progression; post-extinguishment control (checking that there are no hidden hot spots); assessing the temperature of gases and smoke layers; and firefighter training and education. Respondents answered using various combinations of responses, and the analysis identified the following data.

The largest number of respondents agreed with the statement that a thermal camera is especially useful for locating hidden fires (e.g., in walls and ceilings), totaling 46 respondents (90%). A total of 44 respondents (86%) stated that a thermal camera is especially useful for post-extinguishment control. The opinion that a thermal camera is especially useful for locating people in smoke-filled spaces was supported by 43 respondents (84%), while 41 respondents (80%) selected locating the fire source. A somewhat smaller number, 28 respondents (55%), considered a thermal camera especially useful for firefighter training and education. Seventeen respondents (33%) considered a TIC especially useful for assessing structural stability and the temperature of gas and smoke layers. A total of 14 respondents (27%) reported that a TIC is especially useful for locating injured persons in open areas, and 13 respondents (25%) reported that it is especially useful for monitoring fire progression.

The question “6a. Do you believe that, with the assistance of a thermal camera, you identify a fire more quickly and accurately?” was asked to assess the actual effect of thermal cameras in operational interventions using a 5-point scale. Most respondents agreed completely, totaling 38 (75%). Slightly fewer, 12 respondents (24%), agreed by selecting response “4” on the scale, while only one respondent (2%) selected the middle agreement score of “3.”

The question “7a. Do you participate in additional training or exercises with thermal cameras?” was asked to assess the level of continuous improvement in working with thermal cameras. Five possible answers were offered. The largest number of respondents, 15 (29%), answered “No, but I would like to.” Furthermore, 14 respondents (27%) answered “Rarely,” while 12 respondents (24%) answered, “Yes, occasionally.” A somewhat smaller number of respondents, 7 (14%), answered “Yes, regularly,” while a very small number, 3 (6%), answered “No, and I do not see a need for it.”

The question “8a. What helps you most in gaining experience with thermal cameras?” was asked to determine how firefighters most often acquire practical knowledge and experience in using thermal cameras. The offered options included formal training and courses, fieldwork, internal exercises within the department, the use of video materials such as YouTube content, and the exchange of experiences with colleagues, with the possibility of listing additional sources of learning. This approach enables the identification of the most valuable training methods and a comparison between formal and informal firefighter development in the use of thermal cameras. The largest number of respondents, 42 (82%), cited fieldwork as the greatest advantage for gaining experience with thermal cameras. In addition, a large number of respondents (28; 55%) stated that exchanging experiences with colleagues helps them in their work, as do internal exercises within the department (23; 45%). A somewhat smaller number of respondents (17; 33%) identified training and courses as helpful. The smallest number of participants, 5 (10%), considered video materials to be the most helpful.

The question “9a. How much does a thermal camera help you locate hot spots compared with other methods (e.g., visual observation, information from colleagues, sound, smoke, etc.)?” was used to assess the added value of thermal cameras in operational work. A 5-point scale was used, ranging from “1—it does not help me at all” to “5—it helps me extremely.” Most respondents (28; 55%) believed that a thermal camera helps them extremely in locating hot spots compared with other methods; score 4 was selected by 20 respondents (39%), only 2 respondents (4%) selected score 3, one respondent (2%) selected score 2, while no one believed that a thermal camera does not help them at all in locating hot spots compared with other methods.

The question “10a. Which thermal camera functionality do you consider most necessary to improve?” included nine offered answers and the possibility of adding one personal response. Its objective was to gain insight into additional opportunities to develop and adapt the technology to the needs of operational firefighters. The largest number of respondents, 37 (73%), considered the speed of startup and readiness for work to be the most necessary improvement. Thirty-one respondents (61%) saw an opportunity for improvement in display visibility in smoke and darkness; 28 respondents (55%) considered temperature display accuracy to be important; 25 respondents (49%) considered resistance to drops, moisture, and heat to be important; and 24 respondents (47%) selected ease of use/menu/interface. A somewhat smaller number of respondents, totaling 18 (35%), believed there was room for improvement in the ability to record or store images and videos, while 17 respondents (33%) believed the ergonomic design could be improved. Image transmission capability was selected by 16 respondents (31%), while only 15 respondents (29%) believed that there was room for improvement in battery life.

In response to the open-ended question “11a. In which situations do you consider a thermal camera indispensable?”, respondents provided various answers, which had to be categorized for the purposes of analysis. The most frequently mentioned application involved locating and identifying hidden hot spots, for example, in ceiling structures, flue ducts, or roof structures. The second important category was the search and rescue of people in smoke-filled spaces, where respondents emphasized that a TIC is crucial due to reduced visibility. Some responses identified specific types of fires, such as solar panels, electric vehicles, batteries, or hydrogen fires, in which the human eye cannot register the flame. Some respondents emphasized that the TIC is indispensable in more complex fires, while several responses also highlighted the need to improve the equipment itself, such as integrating the TIC into the helmet to make it easier to use (free hands).

In the second part of the research (Group B), responses from 11 respondents whose departments did not have a thermal camera were analyzed. Their attitudes are particularly important because they provide insight into the reasons for not owning this equipment and expectations for its potential application.

The question “1b. State the reason why your department does not have a thermal camera as part of its equipment” was asked to investigate which barriers most influence the lack of thermal cameras in fire departments. The following response options were offered: too high a price, lack of trust in usefulness, negative experiences of others, negative experiences during training or exercises, and the option “I do not know.” Eight respondents (73%) identified the price as too high as the reason for not owning a thermal camera in their institution, while one respondent (9%) identified lack of trust in the equipment as the reason. Three respondents (27%) answered “I do not know.”

The question “2b. Do you think that a thermal camera would improve the effectiveness of your department?” was asked to better understand the opinions of firefighters from departments that do not have thermal cameras. The results of this question provide insight into the extent to which firefighters themselves recognize the added value of a technology that is not yet available to them. Most respondents (7; 64%) agreed with the statement, while 4 respondents (36%) partially agreed.

The question “3b. Is there a plan or desire within the department to procure a thermal camera in the future?” sought to examine long-term expectations and attitudes regarding the importance of including this technology in operational equipment. Five respondents (45%) reported that their institution plans to procure a TIC. In addition, 5 respondents (45%) stated that they desire to procure one but have no concrete plans, while 1 respondent (9%) stated that the department does not plan to procure a TIC.

The question “4b. Have you personally had the opportunity to use a thermal camera in other circumstances (e.g., during training, exercises, joint interventions)?” provides insight into firefighters' personal experience and knowledge, which may influence their perception of the usefulness and need for this technology. Seven respondents (64%) answered affirmatively. Four respondents (36%) had never had the opportunity to use a thermal camera.

The question “5b. In your opinion, how important is a thermal camera for firefighter safety during interventions?” was asked to examine respondents' perception of the contribution of thermal cameras to the safety aspects of operational work. The largest number of respondents, 9 (82%), considered a thermal camera extremely important for firefighter safety during interventions, while 2 respondents (18%) selected the middle value of importance.

4. DISCUSSION

The main elements of the discussion are already contained in the results and clarifications of the questions. The research results confirm all four hypotheses. The results supporting the first hypothesis (H1) confirmed that respondents perceive the technology as a tool that significantly enhances firefighter safety, especially in conditions of reduced visibility and complex interventions. The responses supporting the second hypothesis (H2) emphasized the operational value of TICs: the vast majority of firefighters believe they accelerate and facilitate the location of fires and hidden hot spots, thereby enabling faster decision-making and more effective extinguishment. The third hypothesis (H3) was confirmed across the dimensions of perception and confidence: respondents with TIC experience see TICs as indispensable tools, while those without them nevertheless assess them as potentially very useful. The fourth hypothesis (H4) identified barriers to equipping departments, with financial constraints standing out as the primary reason many fire departments still lack this technology. Additional questions provided a broader picture of firefighters' attitudes. Respondents clearly emphasized which functionalities require improvement.

Although the research provides valuable insight into firefighters' perceptions and experiences with thermal cameras, several limitations should be noted. First, the sample of respondents was limited to a specific number of fire departments, which may limit the generalizability of the results to all fire departments in the Republic of Croatia. Furthermore, some of the questions referred to respondents' subjective assessments, which may always involve a certain level of bias. In addition, the difference between respondents with experience using thermal cameras and those without may mean that some responses are based on assumptions rather than direct experience. To deepen understanding of the role of TICs in firefighting, future research could include a larger, more diverse sample of respondents, including professional and volunteer departments from different regions. In addition to survey questionnaires, to collect more objective data, it would also be useful to conduct field studies or simulation exercises to monitor the actual effectiveness of working with TICs.

5. CONCLUSION

The research clearly shows that TICs are among the most important technical tools in modern firefighting. Their use during interventions, from searching smoke-filled spaces and locating fire sources and hidden hot spots to faster identification of endangered persons, significantly contributes

to the effectiveness and safety of operational personnel. The survey results confirmed all the hypotheses: firefighters who use thermal cameras emphasize their high practical value, while those without this equipment recognize their potential but are mainly prevented from procuring them by the high price. In addition to operational benefits, it is particularly important to emphasize that thermal imaging technology has broader applications beyond firefighting: in emergency medicine, the police, technical services, and specialized units. This confirms its status as a universal tool in crisis situations. Further development of TICs is expected, with an emphasis on integration into helmets, real-time image transmission, and increased device durability, which will further improve their functionality and ergonomics. The research concludes that there is a need for systematic investment in the procurement of thermal cameras and in regular firefighter training. The technology itself provides strong support, but its effectiveness depends on user experience and the ability to correctly interpret infrared images. Therefore, it is necessary for TICs to become part of standard educational programs, and not merely an increase in the quota of additional equipment.

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Professional paper

ORGANIZATION AND FINANCING OF THE FIREFIGHTING SYSTEM IN KARLOVAC COUNTY

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Abstract: *This paper analyses the organizational structure and financing of the firefighting system in Karlovac County in 2024, based on a sample of 22 cities and municipalities. Using demographic, territorial, operational, and financial indicators, the study identifies local government budgets as the primary source of funding for the firefighting system, while funding provided by the Karlovac County Firefighting Association and the Croatian Firefighting Association plays a redistributive and supportive role, particularly in smaller rural local government units. The results confirm the existence of a dual organizational structure: the urban centres of Karlovac and Ogulin account for the largest share of operational activities, whereas rural municipalities have a higher number of firefighters per capita and depend more heavily on supra-local funding sources. The study concludes that the joint establishment of public fire brigades by several local government units could contribute to a more balanced availability of professional firefighting systems throughout the county.*

Keywords: *firefighting; financing; Karlovac County; volunteer fire departments; decentralization*

1. INTRODUCTION

Firefighting plays a vital role in protecting people and property and constitutes an important component of the public safety and humanitarian action system in the Republic of Croatia. In addition to fire suppression, firefighters respond to natural disasters, traffic accidents, floods and various technical rescue operations. The Firefighting Act of 2019 [2] comprehensively regulates the Croatian firefighting system, which is based on the operation of Public Fire Brigades (Javna vatrogasna postrojba – JVP), Volunteer Fire Departments (Dobrovoljno vatrogasno društvo – DVD) and firefighting associations. Local self-government units are responsible for the organization, equipping and financing of firefighting within their respective jurisdictions. Local government budgets represent the primary source of funding, while the decentralization system and equalization grants ensure a minimum level of operational readiness throughout the country [1].

The aim of this paper is to analyse the organizational structure and financing of firefighting in Karlovac County through demographic, geographical, financial and operational indicators and to assess the extent to which the existing organizational and financing model corresponds to local needs.

2. ORGANIZATIONAL AND FINANCIAL FRAMEWORK OF THE FIREFIGHTING SYSTEM

2.1. Organization of the Firefighting System in Karlovac County

The Croatian Firefighting Association (Hrvatska vatrogasna zajednica – HVZ) is the central national authority and the umbrella organization of the Croatian firefighting system [3]. The system comprises 1,772 Volunteer Fire Departments and 109 Public Fire Brigades with approximately 62,000 operational firefighters, the majority of whom serve on a voluntary basis.

The Karlovac County Firefighting Association (Vatrogasna zajednica Karlovačke županije – VZKŽ) serves as the central coordinating organization responsible for organizing and coordinating firefighting activities throughout the county and, within its statutory powers, is accountable to the County Prefect. The organizational structure of firefighting in Karlovac County is highly developed and extensive [4]. The Association comprises a total of 90 Volunteer Fire Departments, 30 of which are designated as central fire stations, in addition to two Public Fire Brigades. The organizational framework includes one Regional Firefighting Association (Područna vatrogasna zajednica – PVZ) in Ogulin, three City Firefighting Associations (Vatrogasna zajednica grada – VZG) in Karlovac, Duga Resa and Ozalj, ten Municipal Firefighting Associations (Vatrogasna zajednica općina – VZO) and four Volunteer Fire Departments (Slunj, Krnjak, Vojnić and Cetingrad) that are directly affiliated with the County Firefighting Association.

The Karlovac City Firefighting Association has the largest number of member organizations, while the Ogulin Regional Firefighting Association integrates several local fire departments and local self-government units (Plaški, Saborsko, Josipdol and Tounj), reflecting a higher level of intermunicipal coordination and territorial integration. A distinctive feature of the organizational structure is that the Volunteer Fire Departments of Slunj, Cetingrad, Krnjak and Vojnić are directly affiliated with the County Firefighting Association, without an intermediate municipal or city firefighting association. This arrangement is partly a consequence of the destruction caused by the Croatian War of Independence and the subsequent post-war depopulation processes.

2.2. Financing of the Firefighting System

Research on the financing of the firefighting system in the Republic of Croatia remains relatively limited [7]. Between 2003 and 2015, expenditure on the decentralized firefighting function increased substantially, rising from HRK 79 million to HRK 302 million. As a result, firefighting became one of the most financially significant decentralized public functions, accounting for approximately 15% of the total decentralized funds allocated. In Karlovac County, however, average firefighting expenditure has declined markedly since 2010, indicating a reduction in per capita financial expenditure in the more recent period.

The Croatian firefighting financing system is based on a dual funding model [2]. Public Fire Brigades are financed by their founding local self-government units through the system of decentralized functions and equalization grants from the state budget, whereas Volunteer Fire Departments and firefighting associations are financed predominantly from local government budgets. Baričević [5] emphasizes the need to develop a more efficient organizational and financing model through stronger cooperation among local self-government units, while Popović [6] points to a potential financial imbalance between professional and volunteer firefighting resulting from the concentration of decentralized funding on Public Fire Brigades.

By a decision of the Government of the Republic of Croatia, minimum financial standards were established for the financing of 75 Public Fire Brigades in 2024, with a total minimum funding standard amounting to EUR 47.6 million [7]. Revenue for financing the decentralized firefighting function of Public Fire Brigades is primarily secured through an additional 1% share of personal income tax revenue. Where these funds are insufficient, the difference is covered by equalization grants from the state budget. In the Croatian Firefighting Association's 2024 budget, these equalization grants amount to EUR 33.1 million, representing approximately 70% of the total minimum funding standard [3].

The financing of the Karlovac County Firefighting Association is provided primarily from the Karlovac County budget, from which a total of EUR 334.3 thousand was allocated to firefighting activities in 2024. [6]. Nearly one-half of these budgetary resources was directed towards co-financing the activities of the Association's member organizations, while the remaining funds covered expenditures that indirectly support their operations.

A review of the available literature and official sources indicates that, although the financing of the Croatian firefighting system is clearly regulated by legislation, obtaining a comprehensive overview of financing at the local level is often difficult due to the uneven availability of financial data. Accordingly, this study is based on the assumption that the organizational structure of the firefighting system in Karlovac County is determined not only by the legislative and financial framework, but also by the spatial distribution of the population, the size of the territory, the number and types of firefighting organizations and the actual operational needs at the local level.

3. DATA

The analysis in this paper is based on data for 2024 and covers 22 cities and municipalities in Karlovac County. Although the analysis covers 22 cities and municipalities, the data in Table 1 are presented according to the organizational units responsible for coordinating and delivering firefighting services. The financing of firefighting at the local level was analysed based on budgetary data published on the websites of municipalities and cities, primarily through the functional classification 032-fire protection services. Other funding from the VZKŽ and HVZ was taken from the VZKŽ's 2024 report. Data on the organisation and operations of the firefighting system was also collected from the VZKŽ report, while data on the population and area of the cities and municipalities was taken from official sources of the State Statistical Office.

The analysis of the non-financial indicators of the Karlovac County firefighting system was conducted based on data on population, the area of local government units, the number and share of fire incidents, and the number of operational firefighters in total and per 100 inhabitants. The indicators examined provide insight into the demographic, territorial and operational characteristics of the fire service in Karlovac County.

The financial analysis of the Karlovac County firefighting system was conducted based on six key financial indicators: local firefighting funding, other sources of funding, the funding ratio (share of other funding in local funding), total funding, the share of total funding, and funding per capita. The aforementioned indicators provide an insight into the structure and intensity of firefighting funding in the municipalities of Karlovac County.

4. RESULTS

Table 1: Demographic, operational and financial indicators of the Firefighting system in Karlovac County

Organizational unit	Population 2021	Area km²	Fire incidents	Share of incidents (%)	Number of firefighters	Firefighters per 100 inhabitants	Local funding (€)	Other funding (€)	Share of other funding in local funding (%)	Total funding (€)	Share of total funding (%)	Funding per inhabitant (€)
VZG Karlovac	49,377	401	475	48.82	364	0.74	2,928,333.15	68,972.40	2.36	2,997,305	57.17	60.7
VZG Duga Resa	10,212	59	58	5.96	67	0.66	145,595.00	9,080.70	6.24	154,675.70	2.95	15.15
VZG Ozalj	5,837	179	41	4.21	125	2.14	138,414.00	30,102.95	21.75	168,516.95	3.21	28.87
DVD Slunj	4,192	401	62	6.37	19	0.45	116,015.62	2,299.00	1.98	118,314.62	2.26	28.22
VZO Barilović	2,691	65	18	1.85	50	1.86	135,650.00	10,128.70	7.47	145,778.70	2.78	54.17
VZO Bosiljevo	1,053	114	10	1.03	53	5.03	44,334.12	8,375.77	18.89	52,709.89	1.01	50.06
DVD Cetingrad	1,863	181	12	1.23	24	1.29	28,500.00	0	0	28,500.00	0.54	15.3
VZO Draganić	2,741	72	17	1.75	35	1.28	79,000.00	9,087.72	11.5	88,087.72	1.68	32.14
VZO Generalski Stol	2,642	100	6	0.62	49	1.85	52,000.00	23,906.81	45.97	75,906.81	1.45	28.73

Organizational unit	Population 2021	Area km²	Fire incidents	Share of incidents (%)	Number of firefighters	Firefighters per 100 inhabitants	Local funding (€)	Other funding (€)	Share of other funding in local funding (%)	Total funding (€)	Share of total funding (%)	Funding per inhabitant (€)
VZO Kamanje	827	32	1	0.1	52	6.29	13,500.00	2,784.71	20.63	16,284.71	0.31	19.69
DVD Debela Kosa	1,533	138	15	1.54	30	1.96	36,914.02	0	0	36,914.02	0.7	24.08
VZO Lasinja	1,322	72	10	1.03	42	3.18	13,115.00	828.30	6.32	13,943.30	0.27	10.55
VZO Netretić	2,409	126	26	2.67	81	3.36	75,844.06	13,056.46	17.21	88,900.52	1.7	36.9
VZO Rakovica	2,097	261	25	2.57	47	2.24	53,835.96	0	0	53,835.96	1.03	25.67
VZO Ribnik	362	40	2	0.21	33	9.12	4,420.86	0	0	4,420.86	0.08	12.21
DVD Vojnić	3,764	240	42	4.32	22	0.58	175,129.18	2,529.82	1.44	177,659.00	3.39	47.2
VZO Žakanje	1,732	46	1	0.1	72	4.16	27,614.44	2,094.9	7.59	29,709.34	0.57	17.15
PVZ Ogulin	18,547	1,205	152	15.62	169	0.91	981,286.15	10,413.41	1.06	991,699.56	18.91	53.47
Total	113,201		973	100.00			5,049,501.56	193,661.65		5,243,163	100.00	

Source: Authors' own work

4.1. Analysis of Non-Financial Indicators of the Firefighting System in Karlovac County

The total number of inhabitants covered by the analysis is 113,201, with the largest share being the City of Karlovac with 49,377 inhabitants, i.e. approximately 44% of the total population of the observed local units. Following Karlovac are the Ogulin Regional Firefighting Association area with 18,547 inhabitants and the City of Duga Resa with 10,212 inhabitants. The demographic concentration of the population in urban areas directly affects the scope of firefighting activities and the organisation of the firefighting system.

In terms of territory, the largest area is covered by the Ogulin Regional Firefighting Association at a total of 1,205 km², while the City of Karlovac, Slunj, Rakovica and Vojnić also have significant areas. The aforementioned data indicate the pronounced spatial dispersion of the Karlovac County firefighting system, particularly in rural and forested areas which require extensive territorial coverage by fire units and volunteer fire brigades.

The total number of recorded fire incidents is 973. The highest number of incidents was recorded in the Karlovac City Firefighting Association area, which accounts for 48.8% of the total. These are followed by the Ogulin Regional Firefighting Association with 15.6%, the Volunteer Fire Departments in Slunj with 6.4%, and the Duga Resa City Firefighting Association with 6.0% of the total incidents. The aforementioned results confirm the concentration of operational burden in the urban and more traffic-intensive areas of the county.

In terms of the number of firefighters, the largest operational system is the Karlovac City Firefighting Association with 364 firefighters, followed by the Ogulin Regional Firefighting Association with 169 and the Ozalj Municipal Firefighting Association with 125 firefighters. At the same time, some smaller rural municipalities have a relatively large number of firefighters in relation to their population. For example, the Žakanje Municipal Firefighting Association has 72 firefighters, Bosiljevo has 53 and Kamanje has 52, despite having a significantly smaller population.

Of particular significance is the indicator of firefighters per inhabitant, which indicates the operational density of the system. The highest values were recorded in Ribnik (9.12 firefighters per 100 inhabitants), Kamanje (6.29), Bosiljevo (5.03) and Žakanje (4.16). On the other hand, urban systems such as Karlovac and Ogulin have lower values for this indicator. Such a structure indicates that rural areas rely more heavily on the voluntary firefighting model and on maintaining territorial coverage, regardless of the absolute number of interventions.

The results of the analysis confirm the existence of a dual structure in the firefighting system in Karlovac County. On the one hand, there are the urban operational centres, primarily Karlovac and Ogulin, which bear the greatest share of the operational burden and the number of interventions. On the other hand, rural municipalities are characterised by a higher number of volunteer firefighters per capita and a pronounced territorial function of the firefighting system. Such a model confirms the territorial and solidarity-based character of the Croatian firefighting system, in which it plays not only a safety role but also an important social and infrastructural one within local communities.

4.2. Analysis of Financial Indicators of the Firefighting System in Karlovac County

Total local funding for firefighting amounts to €5,049,501.56, while additional funding sources, which include funds from the Karlovac County Firefighting Association and the Croatian Firefighting Association, amount to €193,661.65. The total financial resources for firefighting in the period under review amount to €5,243,163.21.

The largest share of the total funding is held by the Karlovac City Firefighting Association with €2,997,305.55, or 57.17% of the total funds. This is followed by the Ogulin Regional Firefighting Association with €991,699.56 and a share of 18.91%, while the other units have a significantly smaller financial share. Such a distribution of financial resources reflects the concentration of population, the number of interventions and the operational burden in larger urban systems.

Local budgets are the dominant source of funding for the firefighting system. The largest local funding is provided by Karlovac and Ogulin. More than €100,000 is allocated to Vojnić, Barilović, Slunj, Duga Resa and Ozalj, confirming the importance of functional classification 032 (Fire protection services) in financing local firefighting systems. At the same time, additional funds from the VZKŽ and HVZ serve a redistributive and supportive function, particularly for certain smaller and fiscally weaker local self-government units. However, for some local units, this effect is entirely absent.

The funding ratio indicator shows the relationship between additional funding sources and local funding. The highest value is recorded by the Generalski Stol Municipal Firefighting Association (45.97%), followed by the Ozalj Municipal Firefighting Association (21.75%), Kamanje (20.63%) and Bosiljevo (18.89%). High values of this indicator indicate a greater dependence of individual rural systems on supra-local funding sources. In contrast, Karlovac (2.36%) and Ogulin (1.06%) show a significantly lower dependence on additional sources, which is linked to a higher local fiscal capacity.

The analysis of firefighting funding in the Karlovac area shows that the largest share of the Karlovac City Firefighting Association's funds is allocated to the financing of JVP Karlovac. Of the almost 3 million euros in total firefighting expenditure, €2,554,667.21 are attributable to JVP Karlovac [8]. Within this amount, €1,039,972.00 constitutes the funds for the decentralised firefighting function, which are secured from the state budget and an additional 1% share of the income tax. Although a portion of the aforementioned funds is of state origin, they are disbursed via the Karlovac City budget as the unit's founder and are subsequently transferred to JVP Karlovac. A similar funding model is also present in the City of Ogulin, where the funds for the decentralised firefighting function are allocated to JVP Ogulin via the city's budget and the Ogulin Regional Firefighting Association. This indicates a greater influence of other funding from the state for the purpose of decentralisation, which is then displayed locally.

Per capita funding further confirms the differences between urban and rural systems. The highest per capita funding is achieved by Karlovac at €60.70 per inhabitant, followed by Barilović (€54.17), Ogulin (€53.47), and Bosiljevo (€50.06) and Vojnić (€47.20). The high values in smaller rural municipalities can be explained by the need to maintain operational readiness and territorial coverage, regardless of the relatively small number of inhabitants.

On the other hand, the lowest per capita funding values are recorded in Lasinja (€10.55), Ribnik (€12.21), Duga Resa (€15.15) and Cetingrad (€15.30). The aforementioned differences indicate an uneven fiscal and operational structure of the Karlovac County Firefighting Association.

The results of the financial analysis confirm that the firefighting funding system in Karlovac County is not solely proportional to population or the number of interventions, but reflects a combination of local fiscal capacity, territorial coverage, and the redistributive function of the county and national firefighting associations. This confirms the solidarity character of the firefighting financing system, particularly in the county's rural and demographically weaker areas.

5. CONCLUSION

An analysis of the financing and organisation of the firefighting system in Karlovac County shows that the existing system is well regulated, particularly following the enactment of the new Fire Service Act. However, the research findings suggest that there is scope for further improvement in the organisation of firefighting at the local level. Examples from the Ogulin Regional Firefighting Association and JVP Karlovac and JVP Ogulin show that cooperation between multiple local authorities can contribute to the more effective organisation and financing of firefighting activities.

National data indicate that the distribution of Public Fire Brigades varies across Croatian counties, while Karlovac County has two Public Fire Brigades [4,9]. In Karlovac County, the area of Slunj, Cetingrad, Rakovica, Krnjak and Vojnić is particularly notable. This area covers a large expanse and has a population of over 10,000, yet it has a relatively small number of volunteer fire brigades. This situation can be partly linked to the consequences of the Homeland War, but also to the lack of a developed firefighting tradition in certain areas. Additionally, potential candidates include Ozalj and Duga Resa, along with their surrounding municipalities, as the two remaining towns in Karlovac County.

The results of the research suggest that a model could be considered whereby multiple local authorities would jointly establish public firefighting brigades, whilst retaining and strengthening existing volunteer fire brigades. Such a model could contribute to a more equitable availability of professional fire protection, particularly in rural and remote areas where public firefighting brigades often cannot intervene in a timely manner without the assistance of local volunteer associations.

Of particular importance in this regard is the fact that Karlovac County covers a large and geographically dispersed area, while the population is concentrated in a few urban centres. Under such conditions, it is essential to ensure an adequate level of fire protection across the entire county, with voluntary fire brigades continuing to play an important role within the firefighting system. Strengthening the decentralised function of the firefighting system and developing new organisational models could contribute to the more effective use of available financial and human resources.

Future research should cover a longer period to analyse in more detail the trends in firefighting funding and the effects of the existing organisational model on the efficiency and availability of fire protection.

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Professional paper

THE SPARK PROJECT: A MONITORING AND ADAPTATION SYSTEM FOR CLIMATE-RELATED WILDFIRE RISK IN KARLOVAC COUNTY

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Abstract: *Climate change is increasing wildfire danger in regions beyond traditionally fire-prone Mediterranean areas. Karlovac County is a relevant study area due to its high forest cover, heterogeneous terrain and karst characteristics. The SPARK project aims to enhance regional resilience to climate-related wildfire hazards by integrating field measurements, laboratory analyses, meteorological monitoring, remote sensing and GIS-based spatial modelling. Planned outputs include high-resolution wildfire hazard maps, a GIS-based monitoring and early-warning prototype, a spatial database and climate-adaptation recommendations for spatial planning, vegetation management and civil protection. As the project is in its initial implementation phase, this paper presents its objectives, planned methodology and expected outputs.*

Keywords: *wildfire risk assessment; remote sensing; climate adaptation; Karlovac County; ERDF programme*

1. INTRODUCTION

Fires are a major natural disturbance of forest ecosystems, affecting ecological processes, biodiversity, forest structure and landscape patterns [1]. The occurrence and behaviour of wildfires are influenced by various environmental and anthropogenic factors, including weather conditions, vegetation characteristics, terrain and human activities [2]. Regions characterised by dry climatic conditions have historically been particularly susceptible to wildfires, including the Mediterranean region, western North America and Australia [3]. However, human-induced climate change is expected to increase wildfire activity globally, including in regions that have been less affected in the past [4]. Projections for Europe indicate an increase in weather-related wildfire danger across the Mediterranean region, while satellite observations and climate analyses suggest a northward expansion of areas exposed to elevated wildfire danger towards Central Europe [5].

These trends are expected to affect the frequency, intensity and spatial distribution of wildfires in Croatia, including continental areas such as Karlovac County. Rising average temperatures, more frequent heat waves and changes in precipitation and wind patterns may prolong periods of reduced fuel moisture, increase vegetation flammability and create conditions favourable to wildfire ignition and spread. Recent climate analyses indicate that weather conditions associated with wildfire ignition and spread are becoming increasingly important in continental Croatia, highlighting the need to incorporate future climate conditions into regional risk assessment and adaptation planning [6].

Croatia has an established legislative, planning and operational framework for fire prevention, preparedness and disaster risk management. Nevertheless, existing planning instruments could be further supported by spatially detailed, climate-sensitive and locally validated assessment tools. Previous studies have demonstrated the value of multi-source remote sensing for monitoring fire spread and vegetation dynamics [7], as well as the importance of vegetation composition and landscape changes in modelling wildfire behaviour [8]. Croatian research has additionally demonstrated the potential of GIS-based risk assessment, multicriteria analysis and the integration of environmental, historical and operational data for preventive planning and decision support [9-11]. The integration of these approaches with field measurements, laboratory analyses and real-time meteorological observations could therefore complement existing planning instruments and strengthen the scientific basis for wildfire prevention and operational decision-making at the county level.

Against this background, the SPARK project aims to connect scientific research, operational practice and regional management structures through four interconnected components: (1) investigation of the environmental and anthropogenic causes, drivers and ecological consequences of wildfires under changing climatic conditions, (2) development of an integrated monitoring and early-warning framework incorporating spatial mapping and predictive modelling, (3) preparation of climate-adaptation measures and operational recommendations for spatial planning, vegetation management and civil protection, and (4) capacity building through professional training, stakeholder workshops and dissemination of project results.

The SPARK project (reference number PK.3.4.17.0016) is coordinated by Karlovac University of Applied Sciences in partnership with Karlovac County and the University of Zagreb Faculty of Forestry and Wood Technology. The project is co-financed by the European Regional Development Fund and is implemented over a three-year period, from 1 April 2026 to 1 April 2029. Its overall objective is to enhance the resilience of Karlovac County to climate-related wildfire hazards through the development and validation of an integrated monitoring, early-warning and decision-support framework based on the assessment of local risks and vulnerabilities. As the project is currently in its initial implementation phase, this paper presents its scientific rationale, methodological framework, planned activities and expected results.

2. STUDY AREA AND PLANNED METHODOLOGY

2.1. Study Area

Karlovac County covers an area of 3,627 km², representing approximately 6.4% of the total area of the Republic of Croatia. It is one of the larger Croatian counties and is situated at the transition between the karst and lowland regions of Continental Croatia [12]. Biogeographically, the county

extends across the Continental and Alpine biogeographical regions [13]. Forests are the dominant land-cover category, covering approximately 51.46% of the county's territory [12].

The forest vegetation is primarily represented by communities of the order *Quercetalia robori-petraeae* Tx. (1931) 1937 and the suballiance *Luzulo luzuloidis-Fagenion* (Lohm. et Tx. 1954) Oberd. 1957, together with areas of Norway spruce plantations [14]. Although parts of Karlovac County receive relatively high annual precipitation, the karst landscape creates spatially heterogeneous moisture conditions that may influence forest ecosystems and the availability and flammability of forest fuels [12], [15]. Forest structure, vegetation characteristics and forest management practices may additionally affect the accumulation and spatial distribution of combustible material [15].

2.2. Selection of Research Sites and Data Collection

During the initial phase of the project, potential research locations will be identified through a desktop analysis combining forest vegetation types, forest management practices, geomorphological characteristics, climatological data and historical wildfire occurrence. The integration of environmental, historical and spatial data has previously been recognised as an important basis for wildfire susceptibility assessment and preventive planning [9-11]. Existing spatial plans and relevant safety and emergency-management protocols will also be reviewed to identify current planning requirements and opportunities for integrating project results into regional and local systems. These environmental characteristics will therefore be considered when selecting research locations and in the subsequent spatial assessment of wildfire susceptibility.

Based on this analysis, six representative research locations will be selected. Field research will be conducted on 30 experimental plots distributed across natural forests and forest plantations. Each experimental plot will cover an area of 625 m². Plot selection will take into account geomorphology, forest structure, vegetation characteristics, forest management practices and available wildfire occurrence statistics. The selected locations and plots will represent different environmental, vegetation and management conditions within Karlovac County.

Forest stand structure and vegetation characteristics will be assessed on each experimental plot. Field mapping and vegetation surveys will also provide information on combustible vegetation, fuel loads, vegetation succession, the occurrence of invasive plant species and evidence of previous wildfire disturbance. These data will support the analysis of the causes and selected ecological consequences of wildfires.

Unmanned aerial vehicles will be used together with photogrammetric and LiDAR techniques to obtain high-resolution information on vegetation structure and forest condition. Remote-sensing methods, including UAV imagery and LiDAR, are widely used for vegetation and fuel mapping, the assessment of forest structure and monitoring of wildfire-related environmental changes [7,16]. The acquired data will support the assessment of forest condition, potential damage and the effects of climate-related changes on forest ecosystems.

Meteorological data will be collected using monitoring stations installed at the selected research locations. The stations will provide real-time information on local weather conditions relevant to wildfire hazard assessment. These observations will complement available climatological data and support comparisons among the selected research locations.

Samples of live foliage, dead forest litter and soil will also be collected from the experimental plots. Laboratory analyses will include the determination of soil physicochemical properties and the testing of selected fuel characteristics, including ignition delay and burning duration. The quantity

and selected properties of live and dead fuels will be assessed through field sampling and laboratory analysis. Field and laboratory measurements of fuel characteristics and flammability provide important information on ignition potential and support wildfire hazard assessment [15].

2.3. Spatial Data Integration and Modelling

Field measurements, laboratory results, meteorological observations, remote-sensing data and available historical wildfire records will be integrated within a GIS environment. All collected data will be organised within a spatial database to support their analysis and subsequent presentation through the project GIS platform.

The combined dataset will be used to develop and validate spatially explicit models of forest ecosystem susceptibility and wildfire hazard in Karlovac County. GIS-based multicriteria analysis and the integration of environmental and operational data have previously been applied in Croatian wildfire assessment and decision-support studies [9-11].

Available climate projections will be considered in the development of high-resolution maps of future wildfire hazard and fire-smart spatial-ecological models for the simulation of future scenarios. Field observations and remote-sensing data will be used to validate the spatial information produced by the project.

The resulting spatial models, meteorological observations and field data will form the basis of a functional GIS-based prototype for wildfire monitoring, early warning and decision support. The prototype will support the identification of areas exposed to elevated wildfire hazard and the provision of relevant spatial information to county and local authorities and professional services.

The developed fire-smart approach will be tested in the field and adapted for integration into existing county and local systems. Based on the research findings, spatial models, review of planning documents and cooperation with relevant stakeholders, the project will formulate at least five climate-adaptation and/or disaster-risk-reduction measures. The proposed measures will address vegetation and forest-residue management, spatial zoning, recommendations for operational services, integration of wildfire information into spatial planning and the application of digital risk-monitoring tools.

The relationship between the main project components, planned methods and expected outputs is summarised in Table 1.

Table 1: Relationship between SPARK project components, planned methods and expected outputs

Project component	Main data and planned methods	Expected outputs
Investigation of wildfire causes and ecological consequences under changing climatic conditions	Historical wildfire and climatological data; field mapping; forest stand and vegetation surveys; fuel, litter and soil sampling; laboratory analyses; meteorological monitoring	Field-validated dataset on fuel loads, vegetation succession, invasive plant species, soil properties and local meteorological conditions
Development of an integrated monitoring and early-warning system	UAV photogrammetry and LiDAR; remote-sensing data; GIS integration; spatial analysis and predictive modelling; field validation	High-resolution wildfire hazard maps; fire-smart spatial-ecological models; functional GIS-based monitoring and decision-support prototype

Project component	Main data and planned methods	Expected outputs
Development of climate-adaptation measures and operational recommendations	Review of spatial plans and safety protocols; analysis of research findings; field testing of the fire-smart approach; stakeholder cooperation	At least five proposed climate-adaptation and/or disaster-risk-reduction measures; recommendations for spatial planning, vegetation and forest-residue management, operational services and civil protection
Capacity building, knowledge transfer and dissemination	Stakeholder workshops; professional training; scientific publications; conference presentations; organisation and dissemination of project data	Knowledge base and professional guidelines; trained local stakeholders; strengthened interdisciplinary research team; spatial database and publicly accessible project outputs

3. EXPECTED RESULTS AND PROJECT IMPACTS

3.1. Expected Project Results

The SPARK project is expected to produce the following results:

- High-resolution maps of future wildfire hazard in Karlovac County.
- A functional GIS-based prototype for identifying wildfire-prone areas by integrating remote-sensing data, field sampling results, meteorological observations and spatial models.
- A publicly accessible and field-validated dataset containing information on fuel loads, invasive plant species, ecological succession, soil properties and real-time meteorological conditions, thereby contributing to Open Science principles.
- Fire-smart spatial-ecological models for simulating future wildfire scenarios.
- A spatial database containing the collected and derived project data, made available through the project GIS platform.
- A knowledge base containing guidelines for decision-makers and wildfire management professionals, including firefighters and forestry experts.
- At least five proposed climate-adaptation and/or disaster-risk-reduction measures addressing vegetation and forest-residue management, spatial zoning, recommendations for operational services, spatial planning and digital wildfire-risk monitoring.
- Recommendations for the appropriate management of vegetation residues on forest and agricultural land.
- Publication of at least three peer-reviewed scientific papers based on the research findings.
- Presentation of project results at national and international scientific and professional conferences.
- Training of local stakeholders and strengthening of the research and professional capacities of the project partners.
- Establishment of a competitive interdisciplinary research team.
- Improvement of research infrastructure through the procurement of equipment for field and laboratory activities.

3.2. Expected Project Impacts

Following project implementation, impacts are expected at several interconnected levels.

Scientific contribution

The project will provide a scientific basis for spatially explicit assessment of wildfire susceptibility and hazard in forest ecosystems, taking into account the karst landscape, heterogeneous forest structure, vegetation characteristics and local climatic conditions of Karlovac County. The integration of field measurements, laboratory analyses, remote sensing, meteorological observations and historical wildfire records is expected to improve knowledge of the environmental factors associated with wildfire occurrence and its ecological consequences.

Economic contribution

The developed spatial models, hazard maps and GIS tools are expected to support more targeted planning of preventive and mitigation measures. Improved identification of priority areas may contribute to a more efficient allocation of financial, technical and operational resources and potentially increase the cost-effectiveness of wildfire prevention and management at county level.

Environmental contribution

The project is expected to support climate-adapted forest and landscape management, including the management of combustible vegetation and forest residues. The proposed fire-smart measures may contribute to the recovery of native vegetation, the control of invasive vascular plant species and improved soil conservation in wildfire-affected and wildfire-prone areas.

Social contribution

The project is expected to strengthen the resilience of local communities by improving access to wildfire-related spatial information, increasing the capacities of professional and regional stakeholders and raising public awareness of proactive landscape management in the context of climate change. Training activities and stakeholder workshops will support the transfer of scientific knowledge into operational practice.

Strategic contribution

Project results and fire-smart landscape-planning guidelines are expected to provide a scientific and technical basis for the integration of wildfire-risk considerations into relevant county-level spatial, development and climate-adaptation documents, including the Karlovac County Development Strategy and documents related to green infrastructure and spatial planning.

Taken together, the expected project results may establish Karlovac County as a pilot area for the development and testing of digitally supported, climate-adapted wildfire management. The resulting methodological framework and operational recommendations may also be transferable to other Croatian counties facing increasing climate-related wildfire hazards.

4. CONCLUSION

Climate change is expected to increase wildfire hazard in continental regions that have historically received less attention than Mediterranean fire-prone areas. Due to its high forest cover, heterogeneous terrain, karst characteristics and dispersed settlements, Karlovac County represents a relevant area for the development and testing of an integrated wildfire monitoring and climate-adaptation framework.

The SPARK project will combine field measurements, laboratory analyses, meteorological monitoring, remote sensing and GIS-based spatial modelling to improve the understanding of wildfire susceptibility and hazard. The project is also expected to support the development of a prototype monitoring and early-warning system, together with operational recommendations for spatial planning, vegetation management and civil protection.

Because the project is at its initial stage, the presented outcomes represent planned research outputs and expected contributions rather than validated results. Their practical value will depend on the successful integration of multidisciplinary data, field validation and cooperation with local and regional stakeholders. The developed approach may provide a transferable methodological framework for other continental Croatian regions facing increasing climate-related wildfire risks.

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Professional paper

FIRE PROTECTION AS A CORE RULE AND INTEGRAL PART OF THE OCCUPATIONAL SAFETY SYSTEM

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Abstract: *Security systems in a modern working environment require a holistic approach and synergy of various disciplines in order to preserve human lives, workers' health, and property. The aim of this paper is to analyze the correlation, complementarity, and necessity of full integration of fire protection into the comprehensive occupational safety system. Based on the analysis of current legal regulations in the Republic of Croatia, the paper explores how the fire hazard categorization of buildings affects the organization and implementation of occupational safety measures.. The paper elaborates in detail on the overlapping of strategic documentation (risk assessments), the operational implementation of evacuation drills, technical testing, the role of workers' representatives, and the the relationship between fire-related hazards and the classification of certain jobs as jobs with special working conditions in accordance with modern obligations for practical training. In conclusion, the integration of fire protection and occupational safety is not merely a legal obligation, but a prerequisite for creating a safe and sustainable safety culture in business operations.*

Keywords: *occupational safety, fire protection, risk assessment, building categorization, evacuation drills*

1. INTRODUCTION

1.1. Subject and Aim of the Paper

Occupational safety and fire protection measures in a modern workspace form the foundation for preserving the lives and health of workers, as well as material assets. The safety of workers and property in the workplace cannot be viewed in isolation; rather, it requires a comprehensive approach and synergy of various safety-related disciplines. The aim of this paper is to demonstrate why fire protection and occupational safety must be merged into a single integrated system and operate jointly to enhance overall safety.

The paper is based on the thesis that fire risk is not merely a spatial or structural issue, but a hazard to business operations and workers' health, thus becoming a primary safety task. The paper specifically addresses how the legal obligations of employers and building owners change and increase depending on the level of fire hazard. It also explains how these hazard levels directly determine the manner in which occupational safety must be organized.

1.2. Methodology of the Paper

The paper is based on the analysis and interpretation of current laws and bylaws of the Republic of Croatia. The key legal sources used include the Occupational Safety Act, the Fire Protection Act, and the accompanying ordinances governing the classification of facilities and the drafting of general acts. Through a comparative analysis, the paper presents the differences in technical and organizational requirements between high, medium, and low fire hazard facilities, with a special emphasis on how these differences impact the daily management of occupational safety and the obligations of authorized representatives and occupational safety experts.

2. FIRE PROTECTION AS A COMPONENT OF CORE OCCUPATIONAL SAFETY RULES

2.1. Legal Basis and Definition

Pursuant to Article 12 of the Occupational Safety Act, core occupational safety rules encompass technical measures that eliminate or mitigate hazards directly at the source (facilities, technological processes, machinery, and equipment). Within these fundamental rules, the legislator explicitly emphasizes the obligation to prevent fires and explosions, while ensuring safe, unobstructed, and properly marked evacuation and rescue routes.

Consequently, fire protection is not a secondary discipline, but a foundational pillar of core occupational safety rules. The intertwining of these obligations is unquestionable, making the lack of tighter legislative integration surprising. Non-compliance with fire protection requirements may directly compromise the effectiveness of other occupational safety measures and significantly increase the risk to workers and property. Thus, it constitutes a severe violation within the occupational safety system, demonstrating that genuine occupational safety cannot exist without effective fire protection.

2.2. Preventive Obligations of the Employer

The employer has the primary responsibility for organizing and implementing occupational safety and fire protection measures within the workplace, in accordance with applicable legislation. In daily practice, this responsibility manifests through the interaction of both systems:

- Structural and Process Safety: Designing and maintaining facilities to minimize fire risks, directly ensuring safe working conditions.
- Crisis Management Planning: Developing clear, operational evacuation and rescue plans, which is a direct statutory obligation under the Occupational Safety Act.
- Signage and Visibility: Installing standardized, conspicuous, and photoluminescent evacuation signs, which represent a key component of occupational safety signage.

- Technical Systems: Providing sufficient, functional, and regularly inspected equipment (such as fire extinguishers and hydrants) to supply workers with tools for early-stage fire suppression.

2.2. Risk Assessment and Worker Training

Risk assessment is the foundational document of occupational safety used to analyze workplace hazards. Fire risk constitutes one of the most critical threats to life; therefore, it is an integral part of every risk assessment. Failing to minimize these risks technically and organizationally defeats the primary objective of occupational safety—preserving human lives.

Accordingly, employers must train workers to work safely. This education must legally include a practical component: familiarization with the evacuation plan, proper emergency response, and the operation of initial fire extinguishing equipment. A trained worker thus becomes a vital asset in fire prevention, capable of stopping fire spread in its early stages.

3. BUILDING CATEGORIZATION ACCORDING TO FIRE HAZARD AND ITS IMPACT ON OCCUPATIONAL SAFETY ORGANIZATION

Pursuant to the current Fire Protection Act (Official Gazette / Narodne Novine No. 92/10, 114/22) and the Ordinance on the Classification of Buildings, Building Sections, and Spaces into Fire Hazard Categories (Official Gazette No. 62/94, 32/97), the Ministry of the Interior (MUP) issues decisions classifying facilities into four primary categories. This classification depends on the type and quantity of flammable substances, building purpose, surface area, and the number of employees and users. Lower category numbers indicate higher risks and stricter statutory obligations. Consequently, this categorization directly dictates the organizational complexity of the employer's entire integrated occupational safety and fire protection system.

3.1. Category I – Extremely High Hazard

This category encompasses facilities with extreme fire and explosion risks, such as petrochemical plants, oil refineries, and large storage facilities for gases and flammable liquids.• Obligations: Owners must maintain an internal, professional, and permanently on-duty fire brigade within the facility, utilize state-of-the-art automatic fire suppression (sprinkler) and detection systems, and ensure continuous monitoring by safety experts. Connection to Occupational Safety: In these facilities, fire protection and occupational safety functions are fully intertwined. Pursuant to legal regulations, these workplaces are classified as jobs with special working conditions. Due to constant exposure to specific fire and explosion hazards, employees must undergo regular medical examinations at authorized occupational medicine clinics. Furthermore, periodic testing of safety systems and work equipment must be conducted by certified occupational safety and fire protection companies.

3.2. Category II – High Hazard (2a and 2b)

This category includes facilities with high occupancy or complex technological processes, such as large shopping centers, hospitals, hotels, large manufacturing plants, and mills with silos. It is divided into subcategories 2a and 2b based on specific fire load characteristics. Obligations: Facilities classified under categories IIa and IIb must develop a Fire and Technological Explosion Hazard

Assessment and an operational Fire Protection Plan. Legal entities in this category are required to establish a professional fire protection service or employ a fire protection expert (holding a Master's degree in safety engineering or a related technical discipline). This expert must focus exclusively on these tasks and pass the professional exam for fire protection personnel administered by the Ministry of the Interior. Periodic testing of stable fire alarm systems is mandatory at least once a year, supplemented by technical maintenance servicing twice a year. Connection to Occupational Safety: This category creates a direct institutional link. The occupational safety expert and the fire protection expert must collaborate daily in workplace supervision. Furthermore, the inspection results of stable fire alarm systems directly serve as evidence of a safe working environment during occupational safety inspections.

3.3. Category III – Medium Hazard

This category comprises medium-risk facilities, including smaller manufacturing plants, larger office buildings, educational institutions, and warehouses storing non-extremely flammable substances. Obligations: Unlike Categories I and II, entities in Category III are not legally required to draft complex hazard assessments, fire protection plans, or employ full-time fire protection staff. Instead, they must adopt Fire Protection Regulations (a general internal act) governing basic measures and employee conduct. Fire protection duties can be assigned to an employee alongside their regular job (a designated person), provided they pass the Ministry of the Interior's professional fire protection exam for Categories III and IV. Regular maintenance of fire extinguishers and hydrants, as well as conducting evacuation drills, remains mandatory.

- Connection to Occupational Safety: In practice, employers most frequently assign these duties directly to the occupational safety expert or the employer's authorized representative. This achieves full personal integration of both systems within a single individual, who synchronically manages all aspects of worker safety.

3.4. Category IV – Low Hazard

This category applies to facilities with minimal fire risk, such as small offices, agencies, beauty salons, small-scale grocery stores with few employees, and artisan workshops that do not utilize open flames or flammable chemicals.

- Obligations: Regulatory demands are structurally straightforward but remain mandatory for worker safety. The owner/employer must maintain Fire Protection Regulations (a general internal act) or a written Decision on Fire Protection Measures. The primary focus centers on technical prevention: ensuring unobstructed evacuation routes, maintaining functional and serviced fire extinguishers (inspected annually), and providing basic emergency response instructions to employees.
- Connection to Occupational Safety: Technical requirements under Category IV directly correlate with the minimum spatial conditions stipulated by occupational safety regulations. For small employers, a single individual usually manages both occupational safety and fire protection, merging them into a unified framework to ensure business continuity and employee safety.

3.5. Impact of Categorization on Jobs with Special Working Conditions and Training Obligations

The fire and explosion hazards present in a facility may be relevant to determining whether particular workplaces meet the criteria for classification as jobs with special working conditions. Higher fire hazards increase the likelihood that workers will perform duties defined by the Ordinance on Jobs with Special Working Conditions (Official Gazette No. 5/84). Due to elevated fire and explosion risks, these positions mandate strict medical, professional, and educational prerequisites:

- Article 22 of the Ordinance (Handling Explosive and Flammable Substances): Stipulates specific conditions for workers involved in the production, processing, storage, or transport of substances capable of causing fires or technological explosions (typical for Category I and II structures). Workers must undergo mandatory periodic medical examinations every 24 months and meet strict psychophysical requirements.
- Article 26 of the Ordinance (Professional Firefighters): In Category I facilities (refineries, petrochemical plants) where an internal professional fire brigade is legally required, firefighter positions are classified as jobs under extreme stress, with specific age, health, and physical endurance criteria.
- Articles 3 and 4 of the Ordinance (Operation of Energy and Thermotechnical Systems): Operating high-pressure steam boilers or compressor stations directly impacts fire risk. These operators must possess proven vocational qualifications and undergo regular competency evaluations, as operational errors can cause catastrophic fires endangering the entire facility.

Training Obligations Pursuant to Recent Regulatory Amendments

In the context of integrating fire protection and occupational safety, recent updates to occupational safety bylaws—including the modernized Ordinance on Occupational Safety Training and Professional Examinations — introduce critical shifts in employee education

a) Mandatory On-the-Job Practical Training: Under current legal frameworks, safe work training can no longer be purely theoretical. Employers must conduct practical training directly at the worker's actual workstation. In higher-hazard facilities (Categories I, II, and III), this explicitly requires workers to physically walk evacuation routes, learn to activate the nearest manual call points, and master the physical operation of portable fire extinguishers at their specific micro-location.
b) Training for Authorized Representatives and Employers: Recent amendments emphasize that employers and their authorized representatives must undergo more rigorous training programs to independently manage safety systems or supervise personnel. Since fire protection duties in Category III and IV facilities are often delegated to authorized representatives or the employers themselves, this educational requirement merges worker protection concepts with technical fire prevention knowledge (specifically concerning structural elements, equipment, and physics-based systems designed to suppress or contain fire).
c) Digitalization and Traceability (Occupational Safety Information System): New regulations mandate stricter traceability and data logging for training activities within the official information systems of the ministry responsible for labor. Consequently, the dates of safe work training (occupational safety) and the timelines of practical evacuation drills or fire simulations (fire protection) must be precisely synchronized and logged to maintain legal and operational validity, [1, 2, 5].

4. HOW OCCUPATIONAL SAFETY AND FIRE PROTECTION COMPLEMENT EACH OTHER

4.1. Synergy of Strategic Documentation

The systemic connection between occupational safety and fire protection is most evident in the overlapping of documentation. The Risk Assessment, [6] and the Fire and Technological Explosion Hazard Assessment [8] (for Categories I and II) must be in complete alignment. Where the fire and explosion hazard assessment identifies specific fire-related hazards in an area or workplace, those hazards should be appropriately reflected in the occupational safety risk assessment and in the preventive measures prescribed for workers.

This alignment automatically triggers the obligation to implement specialized personal protective equipment, stricter medical examinations for employees, and specific safe work instructions. In Categories III and IV, internal Fire Protection Regulations directly supplement Occupational Safety Regulations to ensure comprehensive coverage of all safety procedures, [7].

4.2. Operational Implementation and Technical Compliance

Operational synergy between occupational safety and fire protection is most clearly demonstrated through three core elements of daily practice:

- Evacuation and Rescue Plans and Practical Drills: This represents the most critical intersection of both systems. Regardless of whether a building is classified under Category II or IV, occupational safety regulations mandate that employers conduct practical evacuation and rescue drills at least once every two years for all workers. In practice, these drills rely entirely on fire protection infrastructure (fire alarms, emergency lighting, and evacuation routes). Through these exercises, workers practice life-saving procedures, demonstrating how technical fire protection systems serve the humanitarian goals of occupational safety.
- Testing of the Working Environment and Equipment: The Occupational Safety Act mandates regular inspection and testing of high-risk machinery and utilities (electrical, gas). Concurrently, the Fire Protection Act requires inspections of stable fire suppression systems, hydrants, and extinguishers. In practice, faulty electrical installations (occupational safety domain) are the leading cause of fires (fire protection domain). Therefore, preventive maintenance and system testing constitute a unified technical measure that simultaneously protects workers from electrical shock and facilities from fire.
- Joint Supervision and Inspection Compliance: During inspections by the State Inspectorate (Labor Inspection for occupational safety), inspectors routinely verify whether evacuation routes are clear and whether workers are trained in initial fire suppression. Although fire protection primarily falls under the jurisdiction of the Ministry of the Interior, failing to implement it results in rigorous penalties from the labor inspection, as an inoperable fire protection system is treated as a direct failure by the employer to provide a safe workplace.

4.3. The Role of the Workers' Occupational Safety Representative in the Context of Fire

Protection The workers' occupational safety representative serves as a vital link between management (the employer) and employees regarding safety matters. Their role, defined by the Occupational Safety Act, directly extends to fire protection through several critical functions:

- Right to Information and Access to Documents: The representative has a statutory right to review the Risk Assessment, the Fire Hazard Assessment, and the Fire Protection Plan (for Categories I and II). They monitor whether the measures outlined in these documents are implemented on-site and ensure that workers are familiar with them.
- Participation in Evacuation Drills: The representative actively participates in planning and analyzing evacuation drills. As a trusted liaison, they motivate workers to take drills seriously and gather feedback on observed deficiencies, such as locked emergency exits, faint alarms, or obstructed corridors.
- Workplace Technical Prevention Control: Since they operate alongside workers daily, the representative is the first to detect potential fire hazards—such as damaged extension cords, improvised electrical appliances in offices (Categories III and IV), and blocked access to fire extinguishers or hydrants. Their duty is to immediately submit written warnings regarding these lapses to the employer's authorized representative or the occupational safety expert.
- Action Through the Occupational Safety Committee: For employers with 50 or more workers, the representative is a mandatory member of the Occupational Safety Committee. During committee meetings, they have the right and duty to address fire protection issues, such as requesting higher- quality flame-retardant personal protective equipment or highlighting inadequate conditions in high-hazard zones.

5. CONCLUSION

All the aforementioned points indicate that occupational safety and fire protection are two inextricably linked systems that must operate in complete synergy within the modern working environment. The artificial separation and division between these fields remain counterproductive, given that their close collaboration elevates overall security to a higher level. Conversely, failing to unite these two disciplines compromises the very integrity of the safety system, [1, 2].

This connection and interdependence are clearly demonstrated through several key arguments:

1. Fire protection constitutes the foundation of a safe working environment.

Fire protection represents an essential component of the technical and organizational measures aimed at ensuring occupational safety. If fundamental fire safety conditions are not met within a facility, the workspace inherently becomes unsafe, which may directly compromise the effectiveness of other occupational safety measures and significantly increase the risk to workers and property.

2. Alignment and complementarity of key documentation.

A Risk Assessment, [6] (as the foundational document of occupational safety) cannot be complete or accurate without fully incorporating data from the Fire and Technological Explosion Hazard Assessment. Only by merging these assessments can an employer obtain a realistic overview of workplace hazards and establish a solid basis for defining jobs with special working conditions.

3. Operational overlapping in crisis situations.

The statutory obligation to conduct evacuation and rescue drills under the occupational safety framework is, in practice, most frequently triggered by fire hazards. Evacuation plans directly depend on the structural and technical solutions of fire protection, such as fire compartments and unobstructed egress routes. Ultimately, regardless of the type of emergency, emergency services and firefighters remain integral to rescuing personnel and securing property.

4. Comprehensive safe work training for personnel.

Educational processes within the occupational safety system must, both legally and practically, integrate theoretical and practical knowledge from the field of fire protection, including the operation of initial fire extinguishing equipment and familiarity with fire protocols. A well-trained and competent worker serves as the vital connecting element between both systems—acting as a primary preventive factor for occupational safety and an active executor of operational fire protection measures when a threat arises. Their knowledge ensures that hazards are mitigated before they escalate to endanger lives and assets.

Conclusively, the integration of fire protection into the comprehensive occupational safety system transcends mere compliance with legal formalities. It represents the only viable and sustainable approach to fostering an integrated safety culture, where the technical compliance of a facility and the protection of workers' health merge into a single mission: the preservation of human lives and business assets.

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Professional paper

AGREEMENT AND DISCREPANCIES BETWEEN COUNTRY-REPORTED FOREST-FIRE STATISTICS AND SATELLITE-DERIVED GWIS INDICATORS IN CROATIA, 2002-2024

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Abstract: *Three annual wildfire datasets for Croatia were compared: country-reported EFFIS statistics, GWIS MODIS burned area (2002-2024), and GWIS MODIS+VIIRS fire-event indicators (2012-2024). Trends were tested with Mann-Kendall and Sen methods; agreement was assessed by correlations, ratios, paired tests and log-scale limits of agreement. Reported burned area showed no significant trend, while reported fire counts declined only over the full 1992-2024 period. Reported and MODIS burned areas ranked years similarly (rho = 0.892) but had a median absolute percentage difference of 41.0%. MODIS+VIIRS area was typically 1.95 times the reported value, whereas event counts were 0.34 of reported fire counts. The sources consistently identified severe seasons but were not numerically interchangeable. Methodologically stable baselines and explicit source uncertainty are therefore essential for fire-risk assessment.*

Keywords: *burned area; EFFIS; GWIS; wildfire statistics; method agreement*

1. INTRODUCTION

Open-space and wildland fires are recurrent threats to ecosystems, settlements, infrastructure, tourism and emergency-service safety in Croatia. The national Disaster Risk Assessment identifies open-space fires among the hazards requiring continuous prevention, preparedness and coordinated response [1]. Effective management of complex fire situations also depends on coordinated action among firefighting commands, civil-protection headquarters and local and national authorities [2]. These operational requirements increasingly rely on timely and internally consistent information about fire occurrence, affected area and seasonal severity.

Two broad families of information are available. National administrations report annual fire counts and burned areas to the European Forest Fire Information System (EFFIS), reflecting national definitions and operational records. Satellite systems provide spatially consistent observations across borders. The Global Wildfire Information System (GWIS) uses the MODIS MCD64A1

product for long-run burned-area estimates and combines MODIS and VIIRS active-fire detections to delineate recent fire events [3-5]. The products differ in sensor resolution, processing logic, event definition and land-cover scope. Satellite burned-area products can miss small or obscured burns, while event-reconstruction products may group multiple detections into a single event [3,4,6]. Data streams that all appear to describe wildfires therefore do not necessarily measure the same statistical object.

The authors' previous study described annual, seasonal and regional wildfire patterns in Croatia using GWIS and national data through 2021 or 2023 [7]. It identified strong interannual variability, coastal concentration of large burned areas and marked seasonality, but did not quantify agreement between national and satellite-derived indicators. Such agreement matters when absolute thresholds, event counts and trend estimates are used in risk assessment, prevention planning and performance evaluation.

This study extends the earlier work through 2024 and asks: (1) what long-term trends are present in the available annual series; (2) how strongly do national and satellite sources agree in ranking severe and mild fire years; and (3) are their absolute burned-area and fire-count estimates interchangeable? The aim is not to designate one source as ground truth, but to identify conclusions that remain stable across methods and those requiring source-specific interpretation.

2. MATERIALS AND METHODS

2.1. Data sources

Three annual data streams were analysed. Country-reported annual burned area and number of forest fires were extracted from the supporting workbook for the report Forest Fires in Europe, Middle East and North Africa 2024 [8]. Complete Croatian series were available for 1992-2024 (33 years). These official figures were supplied through national reporting systems and were not treated as an error-free reference.

Annual GWIS MODIS burned area for 2002-2024 was obtained from the GWIS country-profile data distributed through the Our World in Data interface [9]. The series is based on MODIS burned-area observations and reports shrublands and grasslands, savannas, forests and croplands. Annual total burned area was calculated as their sum. Savannas is retained as a MODIS/IGBP product class and does not denote a Croatian biome.

GWIS MODIS+VIIRS annual burned area and satellite-derived event count for 2012-2024 were obtained from the GWIS seasonal-trend data [10]. GWIS combines MODIS and VIIRS thermal anomalies to delineate fire perimeters; VIIRS provides finer active-fire detection than MODIS [3]. The common comparison periods were 2002-2024 for reported versus MODIS burned area (n = 23), and 2012-2024 for reported versus MODIS+VIIRS area and event count (n = 13). All area values were expressed in hectares.

2.2 Statistical analysis

For each series, the mean, median, sample standard deviation, coefficient of variation, minimum, maximum and share contributed by the five largest years were calculated. Monotonic trends were evaluated with the two-sided Mann-Kendall test [11], and magnitude was estimated by Sen median

slope [12]. No annual series showed significant lag-1 autocorrelation, so pre-whitening was not applied.

Cross-source association was assessed by Spearman rank correlation and Pearson correlation after natural-log transformation. Magnitude agreement was evaluated by the annual satellite-to-reported ratio, its median, the geometric mean ratio, median absolute percentage difference (MdAPD), and a paired Wilcoxon signed-rank test on the log scale. Log-scale Bland-Altman analysis [13] provided multiplicative 95% limits of agreement. The overlap between the five highest-severity years from each source was also reported. Tests were two-sided at alpha = 0.05. Calculations were performed in Python using NumPy, pandas and SciPy.

3. RESULTS

3.1. Long-term variability and trends

Country-reported burned area in 1992-2024 totalled 445,880 ha. The annual mean was 13,512 ha, but the median was only 7,936 ha and the coefficient of variation was 108.5%, indicating a strongly right-skewed distribution dominated by extreme seasons. The maximum was 68,171 ha in 2000 and the minimum 188 ha in 2014. The five largest years accounted for 45.0% of the 33-year total. No significant monotonic trend was detected (tau = -0.152, Sen slope = -151 ha/year, p = 0.223).

The country-reported fire count averaged 241 per year and declined significantly over 1992-2024 (tau = -0.392, Sen slope = -6.50 fires/year, p = 0.001). However, the trend was not significant for 2012-2024 (p = 0.252), and annual burned area per reported fire showed no long-term trend (p = 0.656). The result is therefore sensitive to the observation window and should not be interpreted as a uniform recent decline. Figure 1 contrasts the irregular burned-area peaks with the long-run decline in reported counts.

The MODIS long-run series averaged 10,677 ha/year in 2002-2024 and peaked at 51,475 ha in 2017, with no monotonic trend (p = 0.601). The MODIS+VIIRS series averaged 23,947 ha/year in 2012-2024 and also peaked in 2017, at 87,622 ha, without a significant trend (p = 0.952). The 2017 peak is consistent with the documented severity of the Split wildfire season and exceptional Adriatic fire-weather conditions [14]. Table 1 summarises the main statistics.

Table 1. Descriptive statistics and trend estimates for the analysed annual series.

Series	Period (n)	Mean	Median	Max. (year)	Sen slope/ yr	Kendall tau (p)
Reported burned area (ha)	1992-2024 (33)	13,512	7,936	68,171 (2000)	-151 ha	-0.152 (0.223)
Reported fire count	1992-2024 (33)	241	181	706 (2000)	-6.50 fires	-0.392 (0.001)
GWIS MODIS area (ha)	2002-2024 (23)	10,677	5,560	51,475 (2017)	-81.6 ha	-0.083 (0.601)
GWIS MODIS+VIIRS area (ha)	2012-2024 (13)	23,947	16,503	87,622 (2017)	-142 ha	-0.026 (0.952)
GWIS MODIS+VIIRS event count	2012-2024 (13)	67	47	184 (2012)	-2.18 events	-0.245 (0.246)

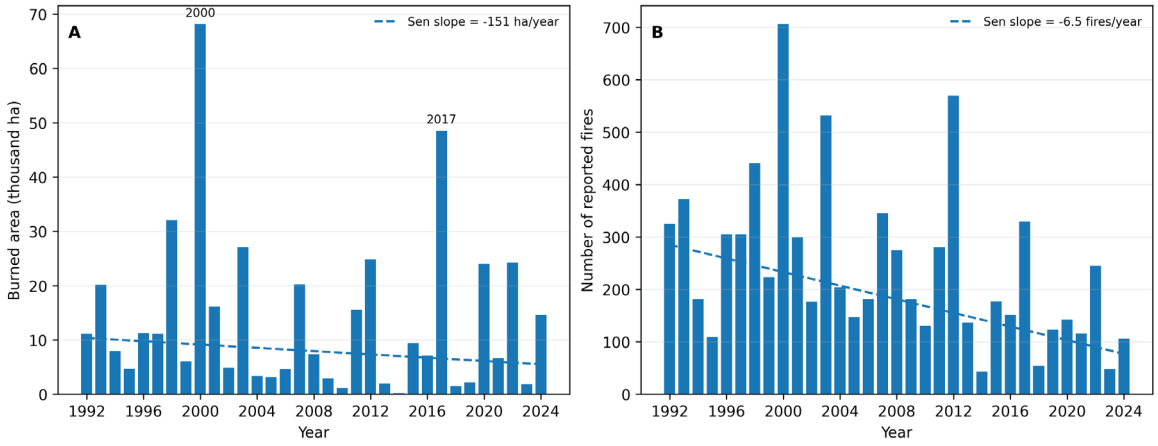


Figure 1. Country-reported annual burned area and fire count, 1992-2024. Dashed lines show Sen slope estimates; the burned-area trend is not statistically significant.

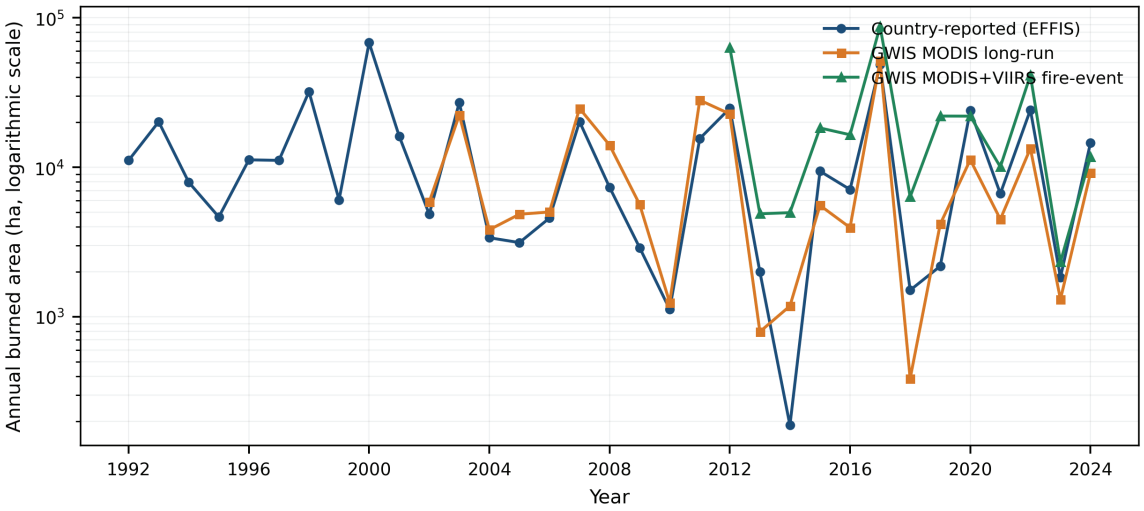


Figure 2. Annual burned-area estimates for Croatia by data source. A logarithmic scale is used because of large interannual variability.

3.2 Agreement between data sources

The sources generally identified the same high- and low-severity seasons, but their absolute values diverged substantially (Figure 2). For 2002-2024, reported and MODIS burned areas showed very strong rank association (rho = 0.892, $p < 0.001$) and strong log-scale Pearson correlation ($r = 0.861$, $p < 0.001$). Their median ratio was 1.06 and geometric mean ratio 0.97. No systematic paired difference was detected ($p = 0.823$), but MdAPD was 41.0% and the 95% ratio limits ranged from 0.26 to 3.67. Three of the five largest years overlapped.

MODIS+VIIRS burned area also correlated strongly with reported area in 2012-2024 (rho = 0.857, $p < 0.001$), and four of the five largest years overlapped. Estimates were nevertheless higher in 11 of 13 years: the median ratio was 1.95, geometric mean ratio 2.48, and paired difference significant ($p = 0.001$). MdAPD reached 94.6%, with 95% ratio limits of 0.38-16.38.

Satellite-derived event counts showed a similar ordering of years (rho = 0.806, p < 0.001) but were lower than reported counts in every comparison year. The median ratio was 0.34, approximately one satellite event for every three reported fires in a typical year. Table 2 gives agreement statistics and Figure 3 displays scatter around the line of equality.

Table 2. Agreement between satellite-derived and country-reported indicators.

Comparison	Period (n)	rho	Median ratio	Geom. Mean ratio (95% LoA)	MdAPD	Wilcoxon p	Top-5
MODIS area / reported area	2002-2024 (23)	0.892	1.06	0.97 (0.26-3.67)	41.0%	0.823	3/5
MODIS+VIIRS area / reported area	2012-2024 (13)	0.857	1.95	2.48 (0.38-16.38)	94.6%	0.001	4/5
MODIS+VIIRS events / reported fires	2012-2024 (13)	0.806	0.34	0.36 (0.12-1.06)	65.6%	<0.001	4/5

Note: Ratio = satellite-derived / country-reported; LoA = multiplicative 95% limits of agreement; MdAPD = median absolute percentage difference.

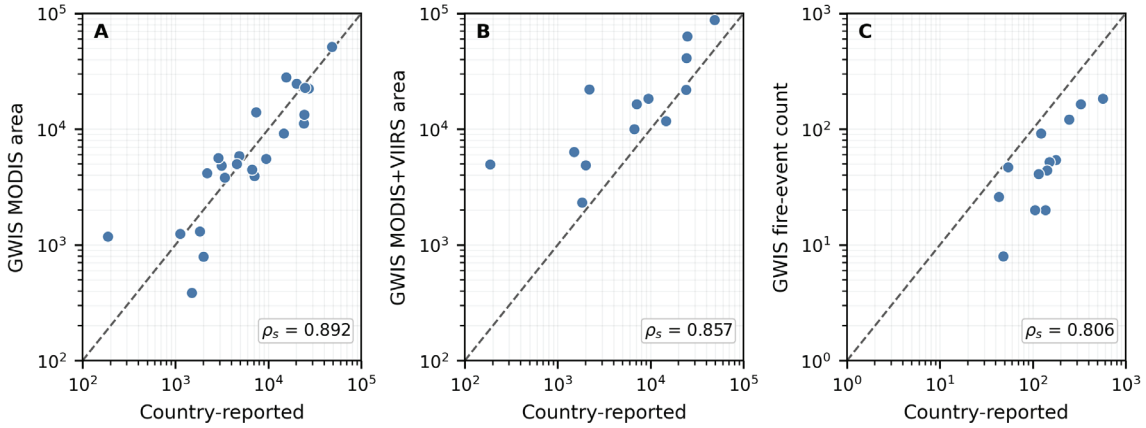


Figure 3. Pairwise agreement on logarithmic axes. The dashed diagonal is the line of equality; rho is Spearman rank correlation.

3.3 Land-cover composition

Across the MODIS long-run series, shrublands and grasslands accounted for 54.0% of burned area, the MODIS savannas class for 28.3%, croplands for 12.2% and forests for 5.5%. The two open-vegetation classes together represented 82.3% of the satellite-derived total. Country-reported forest-fire statistics and a satellite product capturing burns across several vegetation classes therefore do not have identical thematic scope; differences should not be interpreted solely as measurement error.

4. DISCUSSION

The principal result is the distinction between temporal agreement and numerical interchangeability. Rank correlations exceeded 0.80, and the MODIS+VIIRS and reported area series shared four of their five most severe years. Relative indicators such as historical percentile, rank or anomaly class may therefore be robust across sources. High correlation, however, did not guarantee agreement

in hectares or event counts. Wide multiplicative limits and large year-specific differences show that absolute thresholds must remain linked to the dataset from which they were derived.

The long-run MODIS series was closest to country-reported area in central tendency. Its median ratio was near one and no significant paired difference was found. Yet MODIS was higher in 12 years and lower in 11, with large proportional discrepancies in low-area years. Global burned-area products offer spatial consistency, but small burns, cloud or canopy obstruction and classification differences can generate omission and commission errors [4,6]. Absence of average bias should not be mistaken for close annual agreement.

The MODIS+VIIRS event product generally produced larger areas but fewer events. This is plausible because active-fire detections are grouped spatially and temporally to delineate perimeters [3]. VIIRS can identify finer thermal anomalies, potentially expanding detected perimeters, whereas event grouping can combine detections that a national system records as multiple incidents or interventions. The satellite product also includes vegetation fires across land-cover classes, while EFFIS values retain country-specific definitions and reporting practices [8].

No analysed burned-area series showed a significant monotonic trend. This does not imply that climate change is irrelevant to Croatian fire risk. Annual burned area reflects weather, fuel condition, ignition, land management, suppression and reporting. The 2017 Split event illustrates how prolonged heat and drought, extreme fire-weather indices, bura winds and complex terrain can produce an exceptional season [14]. A causal climate analysis would require meteorological, fuel and socioeconomic covariates and lies outside this comparison.

The long-run decline in reported fire counts also requires caution because it disappeared in the 2012-2024 window. It may reflect changes in ignition occurrence, prevention, reporting rules, intervention classification or management effectiveness. Since mean burned area per reported fire did not decline, fewer recorded fires do not automatically imply lower consequence potential.

Four practical implications follow. First, trend indicators should use one methodologically stable source rather than joined series with different sensors or definitions. Second, current MODIS+VIIRS values should be compared with a baseline from the same product. Third, reports should distinguish reported fires, satellite fire events and burned-area pixels. Fourth, dashboards should pair absolute values with historical percentile or rank. A dual-source approach is preferable: national records provide operational context, while satellite products provide independent and spatially consistent observation.

The study is limited to annual national aggregates; individual events could not be matched. Reporting changes cannot be separated from genuine fire-regime change, and the 13-year MODIS+VIIRS interval is short for trend detection. County, meteorological, cause, damage and suppression data were not included, and near-real-time datasets may be revised. These limitations support cautious interpretation but do not alter the central finding that sources can rank seasons similarly while producing non-equivalent absolute values.

5. CONCLUSION

Country-reported EFFIS statistics and satellite-derived GWIS products provide complementary rather than interchangeable descriptions of Croatian wildfire activity. They strongly agree on the relative ordering of years but differ substantially in burned area and event count. The long-run MODIS product is appropriate for consistent historical monitoring, while MODIS+VIIRS supports recent situational assessment; neither should be merged uncritically with national records. Fire-risk studies should name the statistical object measured, retain one product for trend analysis and quantify source-dependent uncertainty whenever absolute values are compared.

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Professional paper

TECHNICAL AND OTHER INTERVENTIONS BY FIREFIGHTING UNITS AND THEIR ROLE IN THE CIVIL PROTECTION SYSTEM

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Abstract: *The fire department system is based on a threat assessment, a fire protection plan, and a fire plan primarily for the purpose of prevention and action in the event of fire and technological explosion. However, fire departments conduct diferentf types of interventions in their activities. Only about 40 percent are fire interventions. Among the most significant are technical interventions to rescue people and property without the presence of fire, in which case fire departments also function as a significant part of the civil protection system. This paper examines the role and status of fire departments within the civil protection system, providing an overview of the operations conducted by the Public Fire Department and the voluntary fire companies of Petrinja during the 2020 earthquake. It places particular emphasis on the coordination of emergency forces, the delegation of tasks, and the authority exercised by the commander of the Petrinja Public Fire Department.*

Keywords: *civil protection, fire departments, technical interventions, earthquake, Petrinja*

1. INTRODUCTION

In the Republic of Croatia, firefighting is defined under Article 1, paragraphs 2 and 3 of the Firefighting Act as a professional and humanitarian endeavor of national interest [1]. This activity encompasses fire prevention, suppression, rescue operations, and the provision of technical assistance on both land and sea. The organization of firefighting units at the local and regional government levels is determined by threat assessments, fire protection plans, and specific firefighting strategies, aimed primarily at preventing and responding to fires and technological explosions. Article 134 of the Constitution of the Republic of Croatia assigns firefighting responsibilities to local self-government units as part of their fire protection duties. This provision also places civil protection under local jurisdiction. The Act on Local and Regional Self-Government mandates that cities and municipalities organize civil protection systems, for which local voluntary and public fire brigades serve as the legal foundation. [2] Fire brigades and related organizations are integral to the civil protection system. According to Articles

20 and 24 of the Act on the Civil Protection System, firefighting forces are recognized as a primary operational component for executing emergency measures.[3] Fire brigades are required to operate within a unified response framework for major accidents and disasters, coordinated by civil protection headquarters, while continuing to adhere to specific regulations governing the firefighting sector. Furthermore, national strategic and operational planning documents designate fire brigades and state intervention units as the primary executors of technical and rescue tasks. At the operational level, this integration is institutionalized by the automatic appointment of fire brigade commanders (at local, county, and state levels) as members of their respective Civil Protection Headquarters. Additionally, the firefighting reporting system (193) is directly linked to and coordinated with the single European emergency number (112), which is managed by the Civil Protection Directorat

2. OPERATION OF FIRE DEPARTMENTS AS PART OF THE CIVIL PROTECTION SYSTEM

2.1. The type of fire brigade's intervention

Fire departments perform a wide range of duties; among the most critical are technical interventions, rescuing people and property in non-fire scenario, which position these departments as a cornerstone of the civil protection system. According to the 2022 Standard Operating Procedures Ordinance [4], fire service operations are classified into four categories: fire interventions, technical interventions, hazardous substance incidents, and other interventions. Previously, these were statistically grouped into three categories: fire, technical, and others. The National Fire Protection Strategy (2013–2022) [5] noted that "other interventions" accounted for exactly 31.5% of all operations in the Republic of Croatia. Within this strategy's decade-long analysis, fires comprised 68.5% of total interventions, while technical interventions (including traffic accidents, floods, environmental hazards, and structural rescues) and various forms of technical assistance made up the remaining 31.5%. Comparative data from 2019 to 2020 shows a significant shift: technical interventions rose from approximately 10,400 to over 17,500 (an increase of over 46%, driven by high-altitude work, chimney removals, and rubble rescue), while fire interventions decreased slightly from roughly 14,200 to 13,500. Additionally, "other" interventions rose from 3,500 to over 5,000, largely due to pandemic-related logistical tasks such as decontamination, equipment transport, and checkpoint monitoring. Consequently, the total national intervention volume grew by approximately 30%, rising from 28,100 to over 36,000 [6]. Comparing 2020 to 2021, statistical data indicates a slight decline in technical interventions from roughly 17,500 to 16,0, though figures remained high due to ongoing recovery efforts in the Banovina region. Conversely, fire interventions saw a significant increase from 13,500 to over 15,200, attributed to a dry summer and a rise in vegetation fires. Overall, national interventions grew from approximately 36,300 to over 38,400, an increase of about 6% [7].

Table 1: The share of intervention number in total , in accordance with intervention type. Source: own work

Time	Total number of interventions	The share of fire intervention	The share of technical intervention	The share of other intervention	The share of technical and other intervention
2013.–2022.	-	68,5 %	-	-	31,5 %
2019.	28.100	50,5 %	37,0 %	12,5 %	49,5 %
2020.	36.300	37,2 %	48,2 %	14,6 %	62,8 %
2021.	38.400	39,6 %	41,7 %	18,7 %	60,4 %

Public statistical data show a rise in total fire department interventions between 2019 and 2021, with the share of technical and non-fire-related operations nearly doubling. This trend is directly linked to the extended recovery efforts following the devastating earthquakes in Zagreb and Petrinja.

2.2. Fire and civil protection system in the Sisak-Moslavina County at the time of the earthquake

Sisak-Moslavina County covers an area of 4,468 km² and, according to the 2011 census, has 172,439 inhabitants. Sisak-Moslavina County consists of 456 settlements organized into 19 local government units (LGUs), 7 cities and 12 municipalities. In total, 20 LGUs have 227 members of the civil protection staff. [8] In the area of Sisak-Moslavina County, there are 500 members of the fire brigade (public fire brigades - JVP and voluntary fire brigades - DVD), 30 members of the Croatian Mountain Rescue Service (HGSS), and 300 members of the Croatian Red Cross (HCK). The cities of Sisak, Petrinja, and Glina have organized general-purpose civil protection units and have a total of about 1,000 members of the civil protection system. [8]. The civil protection system in the City of Petrinja at the time of the devastating earthquake on December 29, 2020, was legally defined and organized according to the then-applicable national laws and local planning acts adopted immediately before or during 2020. It is important to note that at that time, the COVID-19 pandemic was also in effect, so the system functioned under specific decisions regarding movement restrictions. Given that the crisis situation exceeded the capacities of local self-government, state acts were also activated, namely the Civil Protection System Act, which serves as the basis for the law defining the method of coordination between the city, county, and state levels. Immediately after the earthquake on December 29, 2020, the National Headquarters abolished the mandatory e-passes that had been in force until then due to the COVID-19 pandemic, in order to enable the unhindered passage of emergency services and volunteers toward Petrinja. Immediately after the earthquake, on January 4, 2021, the Croatian Government adopted a Decision declaring a disaster [9], which established a special Headquarters for eliminating the consequences of the disaster, headed by Tomo Medved, thus formally taking over the management of the system in Petrinja from the state.

2.3. Petrinja earthquake and the response of the civil protection system

On 28 December 2020, at 6:28 a.m., an earthquake measuring 5.0 on the Richter scale was recorded, causing minor damage to buildings (mostly chimneys and roofs of residential buildings), and prompting the call to the Petrinja area of local volunteer fire departments and several units with rescue and height-working vehicles from outside the City of Petrinja's area of operation. [10] Following the earthquake on 28 December 2020, operators of the Sisak and Zagreb County Civil Protection Centers received hundreds of calls from citizens regarding damage to buildings, collapsed chimneys, and roof tiles in the areas of Glina, Petrinja, and Sisak. According to available data, no people were injured and no houses collapsed in the earthquake. Through the County 112 Centers in Zagreb and Sisak, emergency services were promptly activated and immediately went to the field employees of the Civil Protection Service Sisak of the Civil Protection Directorate, firefighters of the Public Fire Brigades (JVP) and Voluntary Fire Brigades (DVD), and employees of utility companies in the cities of Sisak, Petrinja, and Glina. A total of 90 members of the operational forces worked to eliminate the consequences of the first earthquake. Priorities included marking endangered areas where there was a risk of further harm to passers-by on sidewalks, while utility companies removed plaster and other construction materials from public areas. The Civil Protection Directorate immediately mobilized ten structural engineers from the Faculty of Civil Engineering and three members of the State Intervention Unit for Civil Protection (DIP CZ) with four vehicles, who

were sent to the earthquake-hit area. All activities in the field were coordinated by the Civil Protection Headquarters of Sisak-Moslavina County with the civil protection headquarters of the cities of Sisak, Petrinja, and Glina, and with other civil protection headquarters of the local self-government units affected by the earthquake. In the morning hours, citizens were able to report damage via the website of the City of Sisak, as well as via published telephone numbers for the areas of the cities of Sisak, Petrinja, and Glina. [4] The Director of the Civil Protection Directorate, Dr. Damir Trut, held an operational meeting with the Civil Protection Headquarters of Sisak-Moslavina County at 11:30 a.m. on 29 December 2020, with the aim of defining priorities and coordinating further activities in eliminating the danger and repairing damage after the 28 December earthquake. [11]

Immediately after the meeting, on 29 December 2020 at 12:19 p.m., the town of Petrinja was hit by a powerful and devastating earthquake measuring 6.2 on the Richter scale, with an epicenter 6 km from Petrinja. [10] This earthquake was followed by numerous smaller tremors, and by 6:00 p.m. on the same day, 16 more earthquakes with magnitudes greater than or equal to 3.0 on the Richter scale had occurred. [4] The 112 County Centers in Zagreb and Sisak and the National Civil Protection Operations Center (OCCZ) immediately activated all operational forces of the civil protection system at all levels: civil protection headquarters, fire department operational forces, the Croatian Red Cross, the Croatian Civil Protection Service, and civil protection system participants, including the Croatian Army, the police, and the emergency medical service. The activation procedure for all civil protection system participants was carried out in accordance with planning documents and standard operating procedures. [12] The devastating earthquake caused technical difficulties at the 112 Sisak County Center, and the 112 Zagreb County Center promptly took over the work of both centers at locations in Sveta Nedjelja and the headquarters of the Civil Protection Directorate in Zagreb, with a total of 15 analyst operators. On the same day, the 112 Zagreb County Center received about 2,500 calls and made about 2,000 outgoing calls to emergency services. [8] Given the damage that occurred immediately after the second, devastating earthquake, the event was declared a disaster. At the request of the Commander of the Public Fire Department of the City of Petrinja, all professional Public Fire Departments, voluntary fire departments, and professional industrial units operating outside the area of the city of Petrinja were alerted and called for assistance, enabling them to send people and equipment to help in the rescue and evacuation of a large number of endangered residents. [11] At its peak, around 100 members of the Croatian Civil Protection Department were deployed in the field, supported by 80 staff from the Civil Protection Directorate headquarters, 450 members of the Croatian Mountain Rescue Service (HGSS) with 18 search dogs, 590 employees and volunteers of the Croatian Red Cross, 800 firefighters with 11 search dogs, 200 members of the police, and 300 members of the Croatian Army, while around 300 construction experts from the Croatian Earthquake Engineering Center were available. In addition to 55 teams from the Sisak-Moslavina Institute for Emergency Medicine, 65 additional teams of the out-of-hospital emergency medical service from all over the Republic of Croatia participated in providing emergency medical care in the areas affected by the earthquake. [8]

2.4. Participation of fire brigades in eartquake santion

Immediately after the first earthquake on December 28, 2020, more than 80 firefighters from the Petrinja, Novska, and Kutina Fire Departments, as well as the Petrinja, Hrastovica, Taborište, Mošćenica, Nebojan, Mala Gorica, Topusko, Lipovljani, and Hrvatska Kostajnica Voluntary Fire Departments, arrived at the scene with approximately 20 vehicles. Following the earthquake on December 29, 2020, the fire departments immediately began searching the area within collapsed buildings and aiding people in danger. During the afternoon hours, fire departments from other counties arrived in Sisak-Moslavina County with 430 firefighters, 89 fire trucks, and 11 search dogs.

After the rescue of people from the rubble was completed, firefighters worked on removing damaged chimneys and other structural parts of buildings, repairing dangerous structures, transporting drinking water, clearing roads, and transporting and delivering supplies to the affected population [13]. In the first three months, the operational fire brigade carried out over 12,600 interventions and tasks [8]. Statistical indicators testify to the fact that this was an unprecedented event and an extraordinary situation in which fire departments carried out a huge number of interventions over a long period of time in a highly professional manner [14]. Thus, the average annual number of all types of fire interventions in Sisak-Moslavina County (2010–2018) was 1,500, and the total number of interventions carried out in Sisak-Moslavina County over a period of 32 days (from December 28, 2020, to January 28, 2021) was 11,727. During that period, the cumulative number of firefighters who participated was 10,378, the cumulative number of fire engines deployed was 2,748, and an additional 1,101 interventions were carried out in the following 38 days. Therefore, the total number of interventions in Sisak-Moslavina County within a period of 69 days (from December 28, 2020, to March 6, 2021) was 12,828, with a total cumulative number of 12,033 firefighters and 3,384 fire engines deployed, an increase of 4,435%, which is a historic and extreme percentage increase in the number of interventions on an annual basis in Sisak-Moslavina County caused by an earthquake [15].

2.5. Public powers of the fire brigade commander

In order for fire departments to successfully rescue people and property, the fire chief has extremely broad and legally defined public powers so that he can act quickly in crisis situations, save human lives, and prevent further damage. In specific circumstances, and based on the Fire Act [16] and in the event of earthquake damage (such as the removal of buildings or parts of buildings that are at risk of collapse), the fire chief may, on the basis of his public authority, independently take the following actions: order the partial or complete demolition of buildings or other structures that directly endanger the lives of people, passers-by, or firefighters (e.g., after an earthquake, a wall, chimney, or entire roof threatens to fall onto a public area); manage private and public property (e.g., order a forced entry into any locked or enclosed space—apartment, house, business premises—if he suspects that human life is at risk there or if this is the only way to remedy the danger); use other people's resources (e.g., temporarily seize or use vehicles, machinery, and other material assets of legal or natural persons); restrict movement and evacuation (e.g., set up a security zone and prohibit access to all unauthorized persons); order the emergency evacuation of people and animals (e.g., if he estimates that an unstable building could collapse on them); turn off utility infrastructure (e.g., independently or through competent services such as HEP or gas plants, order the immediate disconnection of electricity, gas, or water, or the interruption of traffic on nearby roads to ensure the safe removal of rubble); and mobilize citizens (e.g., in extremely difficult situations such as catastrophic earthquakes, he can temporarily mobilize adult, able-bodied citizens who happen to be nearby to help in clearing up, transporting equipment, or rescuing the injured).

In the case of the Petrinja earthquake, the emergency fire intervention itself and the extraordinary public powers of the fire intervention leader began immediately on 28 and 29 December 2020. Formally and legally, these lasted in the field in the form of extraordinary command until 30 January 2021, at which point the Government of the Republic of Croatia adopted a Decision on the declaration of a disaster in the area affected by the earthquake [9]. This transitioned system from the operational phase of emergency intervention to the long-term phase of regular rehabilitation, which also ended the extreme emergency powers in the field.

The exact timeframe and legal-operational course of the intervention and authority can be presented as follows:

1. Period from the first earthquake on December 28, 2020, until the establishment of the Headquarters for Eliminating the Consequences of the Earthquake Disaster on January 4, 2021.

In the first phase, public authority (orders to demolish threatened buildings, evacuation orders, forced entry into buildings, etc.) was exercised by the local and county fire chief through operational zones. Firefighters from all over Croatia were mobilized through the institute of extraordinary dislocation by order of the Chief Fire Chief of the Republic of Croatia.

2. Period from January 4, 2021, to January 30, 2021.

In the second phase, crisis management powers were transferred to the state level and centralized. By decision of the Government of the Republic of Croatia [9] on 4 January 2021, a disaster was declared for Sisak-Moslavina County, and a Headquarters for the Elimination of the Consequences of the Earthquake Disaster was formed. From that moment on, all strategic public powers (decisions on the systematic demolition of entire dangerous blocks of buildings, long-term evacuations, and the mobilization of heavy construction machinery) were transferred to the state Headquarters and authorized civil engineers, while fire commanders (VVI) retained operational powers exclusively at micro-locations of work (individual addresses).

3. Official end of emergency intervention: January 30, 2021.

On 30 January 2021, the Decision on Amendments to the Programme of Measures for the Reconstruction of Buildings Damaged by the Earthquake in the City of Zagreb, Krapina-Zagorje County, and Zagreb County entered into force, officially including Petrinja and Sisak-Moslavina County in the system of reconstruction and assistance. The order and official conclusion of the Chief Fire Commander of the Republic of Croatia and the Disaster Relief Headquarters [20] officially ended the previous model of mass emergency deployment of firefighters from all over Croatia in the Banovina area. The Decision brought three key operational and legal changes for the area of the City of Petrinja:

a) Cessation of emergency command in the field, closure of operational bases where firefighters from other counties were stationed, and the management of interventions returned to the jurisdiction of the domicile forces (Fire Brigade of Sisak-Moslavina County and Public Fire Brigade of Petrinja).

b) Termination of the emergency public powers of the fire brigade commander, including those for the partial removal of parts of buildings (chimneys, roofs, bricks) based on a direct risk assessment for the protection of life. Any further action and complete demolition of severely damaged buildings were transferred to the Construction Sector and the Disaster Recovery Headquarters, which began taking over the work in February 2021 based on expert reports. Any further removal of damaged buildings after January 2021 was transferred to the regular administrative reconstruction procedure under the leadership of the competent ministries.

c) The balance sheet of the first phase was published. In its reports [17], the Croatian Fire Association marked January 30, 2021, as the formal end of the first, most intensive phase of removing the consequences of the earthquake. By that date, a cumulative total of 11,875 interventions had been performed. In legal and public practice after the earthquake in Banovina, sharp disputes, complaints from citizens, and constitutional complaints were recorded, but they were not primarily directed against firefighters; rather, they were against the decisions of state bodies (the Civil

Protection Headquarters of the Republic of Croatia and the Ministry of Construction) that took over demolitions outside the scope of emergency interventions. This transition created three main groups of disputes and legal problems:

a) Demolition without the consent of the co-owner (Case "Petrinjka").

b) administrative disputes due to the implementation of the regular procedure and the issuance of decisions by the building inspection, where many citizens initiated administrative disputes or refused to sign demolition consents because they were afraid that by losing the physical object they would lose the right to a replacement house in the reconstruction process.

c) Requests for a review of the constitutionality of articles of the law regulating reconstruction that enabled the state and the Headquarters to remove private property (buildings) without a lengthy evidentiary procedure and the consent of all heirs.

3. CONCLUSION

Technical and other interventions by fire departments are a secondary, but no less important, part of their work. Fire departments are an integral part and the backbone of the work of civil protection headquarters. However, during 2020 and 2021, due to the devastating earthquakes in Zagreb and Petrinja, fire departments, based on the number of interventions undertaken, carried out the majority of their activities outside their core business of extinguishing and preventing fires and technological explosions. In such circumstances, when carrying out technical and other interventions, intervention managers are also responsible for applying the rules on public authority during interventions, which include actions that, temporarily and due to extraordinary circumstances, call into question basic human freedoms (e.g., freedom of movement) as well as other property rights of citizens (e.g., removal of damaged buildings). The law clearly stipulates that the firefighter, during an intervention, acts as a body with public authority on behalf of the civil protection system. This circumstance excludes illegality, which in turn excludes liability for compensation for damages and criminal liability. Firefighters were authorized to exercise the aforementioned public authority regarding the removal of buildings and parts of buildings in an urgent procedure and without issuing an administrative act until the official end of the emergency intervention, i.e., until 30 January 2021, when the Decision on Amendments to the Program of Measures for the Reconstruction of Buildings Damaged by the Earthquake in the City of Zagreb, Krapina-Zagorje County, and Zagreb County [17] entered into force, officially including Petrinja and Sisak-Moslavina County in the system of state reconstruction and assistance, and when the Order and official conclusion of the Chief Fire Commander of the Republic of Croatia and the Disaster Relief Headquarters were issued [18].

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Professional paper

FLAMBLOCKER CF7 IN ELECTRIC VEHICLE FIRE SUPPRESSION: OPERATIONAL TEST RESULTS AND SAFETY IMPLICATIONS FOR FIREFIGHTERS

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Abstract: *Electric vehicle (EV) fires involving lithium-ion battery thermal runaway present significant challenges for firefighting services due to prolonged suppression, toxic emissions, and the risk of re-ignition. This paper presents the results of an operational test conducted on 20 November 2025 in Karlovac, Croatia, in which Flamblocker CF7, a PFAS-free wetting agent, was applied to a lithium-ion battery thermal runaway in a Renault Megane E-Tech (60 kWh) prototype. The battery was charged to 20% state of charge and thermal runaway was initiated by mechanical puncture. Suppression was completed in 6 min 1 s using 1,980 L of total extinguishing solution containing 6% CF7. No re-ignition was observed during the post-test monitoring period. The findings indicate promising potential for reducing suppression duration and resource use, while further testing under different battery states of charge and vehicle orientations is needed to confirm the results.*

Keywords: *electric vehicle fire; thermal runaway; Flamblocker CF7; firefighter safety; lithium-ion battery*

1. INTRODUCTION

The increasing prevalence of electric vehicles (EVs) on European roads is reshaping the operational demands placed on firefighting services. According to the International Energy Agency, approximately 40 million EVs were in service worldwide in 2023, with projections exceeding 250 million by 2030 [1]. In the European Union, battery electric vehicles accounted for 17.4% of all new vehicle registrations in 2025, while hybrid vehicles, which also carry high-voltage battery systems, reached a market share of 34.5% [2].

In Croatia, the growth of electrified vehicles is clearly reflected in the official vehicle registration data maintained by the Centre for Vehicles of Croatia (CVH). The number of registered battery electric vehicles (BEV) in the M1 passenger car category rose from 1,343 in 2020 to 12,605 in

2025, while total hybrid vehicle registrations increased from 8,080 to 105,729 over the same period, representing a more than thirteen-fold increase in five years [3]. This trajectory means that a rapidly growing share of vehicles on Croatian roads now carry high-voltage traction systems, with direct implications for the frequency and complexity of EV-related incidents encountered by firefighting services.

EV fires differ fundamentally from conventional vehicle fires. Thermal runaway is a self-accelerating exothermic decomposition process triggered by mechanical damage, overcharging, or internal failure of the lithium-ion battery. Once initiated, the fire becomes intense, internally sustained, and capable of re-igniting hours after apparent extinguishment [4–6]. International operational guidance reports that a battery thermal runaway left in free combustion lasts on average about 30 minutes and rarely more than one hour, and advises that if roughly ten minutes of attack with two hoses, corresponding to some 2,500 L of water, produces no significant result, the intervention should move to a controlled-burn strategy while protecting the surroundings [7]. Throughout the event, responding personnel may be exposed to large volumes of highly toxic gases, including hydrogen fluoride (HF), carbon monoxide (CO), and hydrogen cyanide (HCN) [7, 8]. Beyond the suppression phase itself, European guidance recommends that a burned or partly burned electric vehicle be kept in quarantine, under frequent inspection and with a water supply available, for a minimum of ten days because of the risk of delayed re-ignition [9].

This paper presents the methodology and results of an operational test conducted in Karlovac, Croatia, on 20 November 2025, in which Flamblocker CF7 was applied to a real EV battery fire under controlled conditions. The test was carried out by the professional firefighting team JVP Karlovac and observed by fire safety specialists and institutional representatives from Croatia, Slovenia, Bosnia-Herzegovina, and North Macedonia.

2. THERMAL RUNAWAY: HAZARDS AND LIMITATIONS OF CONVENTIONAL APPROACHES

Thermal runaway in lithium-ion batteries is characterised by rapidly escalating internal temperatures, which can exceed 1,000 °C within the battery pack. A key feature of the process is that decomposing cathode materials release oxygen internally, allowing the fire to sustain itself even in low-ventilation environments. This limits the effectiveness of conventional smothering techniques; intensive cooling is a commonly recommended intervention strategy for controlling battery thermal runaway, as oxygen displacement alone cannot stop the reaction [5, 7].

The gas mixture released during a full thermal runaway event has been reported to include major bulk gases such as CO_2 (20–45%), H_2 (15–35%), and CO (10–30%), alongside highly toxic minor components including hydrogen fluoride (HF, 0.1–2%), phosphoryl fluoride (POF_3), hydrogen cyanide (HCN), and nitrogen oxides [8, 10, 11]. Although toxic species constitute less than 5% of the total gas volume, quantitative fire tests on seven types of commercial lithium-ion cells measured HF emissions of 20–200 mg/Wh and POF_3 emissions of 15–22 mg/Wh of nominal battery energy capacity, against an Immediately Dangerous to Life or Health (IDLH) level of 30 ppm for HF and 1,200 ppm for CO [12]. Measurements of particle emissions from battery modules in thermal runaway report size distributions in the submicron range, which present an additional inhalation hazard with deep lung penetration [13].

From a regulatory perspective, many extinguishing agents currently in use contain per- and polyfluoroalkyl substances (PFAS) or other corrosive components. Commission Regulation (EU) 2025/1988 adds entry 82 to Annex XVII to REACH, restricting the placing on the market and the use of firefighting foams containing PFAS at concentrations of 1 mg/L or above (sum of all PFAS) from 23 October 2030. Shorter transitional periods apply to firefighting foams placed on the market in portable fire extinguishers (23 October 2026, and 23 April 2027 for alcohol-resistant foams), while longer periods, up to 23 October 2035, apply to certain uses such as Seveso establishments, offshore installations and military applications [14]. Although the restriction is directed at firefighting foams rather than at wetting agents, it indicates a clear regulatory shift towards fluorine-free products in fire suppression.

3. FLAMBLOCKER CF7: COMPOSITION AND MECHANISM OF ACTION

According to the manufacturer's current Safety Data Sheet, Flamblocker CF7 is a water-based solution of plant extracts and alkali salts of inorganic acids. The SDS states that the product contains no PFAS, PBT substances, foams, or AFFF components, is fluorine-free, and is not classified in any hazard class under Regulation (EC) No 1272/2008. It also reports 100% biodegradability after 21 days according to EN ISO 9439:2000 and indicates that no specific respiratory, hand, eye, or protective clothing requirements apply to handling the product itself [15]. Standard personal protective equipment requirements for firefighters remain applicable during EV battery fire interventions.

The extinguishing mechanism of CF7 operates on two levels. First, the agent substantially reduces the surface tension of the water carrier, enabling rapid penetration into porous and thermally damaged materials. Second, after the carrier water evaporates, a residual thermal buffering layer persists on and within treated surfaces, continuing to absorb heat and suppressing temperatures below the thresholds required for renewed thermal decomposition. This extended cooling effect may contribute to reducing the risk of re-ignition, which remains a persistent limitation of water-only approaches. Water-based agents combined with surfactants or other additives are among the suppression strategies examined in the scientific literature on lithium-ion battery fires [16].

According to the manufacturer's Safety Data Sheet, CF7 is suitable for fire classes A, B, D, and F, as well as lithium-ion batteries, with typical use concentrations of 1–3% for class A fires, 3–6% for class B fires, and up to 12% for class D and F applications [15].

4. OPERATIONAL TEST, KARLOVAC, NOVEMBER 2025

4.1. Test Setup

The test was conducted on 20 November 2025 at the former military facility in Karlovac. The data reported in this section are taken from the operational test report [17]. The test vehicle was a Renault Megane E-Tech 2026 prototype (60 kWh / 160 kW), provided by Renault S.A. Group (Corporate) and previously used in factory crash-test simulations. The battery was new, undamaged, and charged to 20% state of charge.

To initiate thermal runaway, the battery pack was mechanically punctured using an on-site forklift, inducing an internal short circuit. This was a deliberate initiation procedure carried out under controlled test conditions; it does not correspond to the handling of damaged electric vehicles in real incidents, for which European guidance explicitly advises against lifting such vehicles with a forklift [9]. The vehicle remained on its side throughout the test. Suppression was carried out using a standard fire truck with a C-line hose delivering 360 L per minute, fitted with a factory-supplied additive dispenser configured to inject CF7 at a 6% mixing rate. The key parameters of the operational test are summarised in Table 1.

Table 1: Key parameters of the EV battery fire operational test, Karlovac, 20 November 2025

Parameter	Value
Test vehicle	Renault Megane E-Tech (60 kWh / 160 kW), 2026 prototype
Battery condition	New, undamaged; 20% state of charge
Temperature at start of attack	~2,000 °C, external surface reading from thermal imaging camera (full thermal runaway with propagation)
Temperature at end of attack	20 °C (external battery surface)
Total suppression time	6 min 1 s
Total water volume used	1,980 L of total extinguishing solution containing 6% CF7
CF7 mixing rate	6% (118.8 L of CF7 concentrate)
Re-ignition observed	None observed during post-test monitoring (several hours)
Firefighting team	JVP Karlovac, 5-member professional team

4.2. Test Execution and Results

Battery puncture at 10:18 AM triggered immediate thermal runaway, with propagation visible within seconds. The battery began emitting large volumes of toxic and flammable gases, with open flames and intermittent explosive discharges through the puncture sites. Thermal camera readings indicated external surface temperatures of approximately 2,000 °C prior to the onset of suppression; operational guidance notes that the decrease in temperature over time is a more reliable indicator of the effectiveness of an attack than the absolute value [7]. Suppression was initiated immediately after thermal runaway developed and continued until visible combustion had ceased and thermal imaging showed no remaining hot spots. The two-person attack team applied water with 6% CF7 first to the external battery surface, then directed the stream into the open puncture openings to access the battery interior, in line with the recommendation to use fusible or weakened parts of the casing as entry points for extinguishing water [7].

At 5 min 31 s into the attack, open flames were no longer visible, though gas and particle emission continued. A brief second attack lasting 30 s was directed into the battery openings to load additional agent into the battery compartment. At the 6 min 1 s mark, all visible combustion had ceased and gas emission dropped markedly. The attack was halted.

Post-suppression thermal imaging confirmed an external battery surface temperature of 20 °C. The vehicle was kept under observation for several hours after the intervention, and no re-ignition was observed during that period.

5. COMPARATIVE PERFORMANCE AND DISCUSSION

To place the observed CF7 performance in context, Table 2 compares the results of the present operational test with published data for conventional water-based EV fire suppression. Because the test conditions differ between sources, the comparison should be interpreted with caution.

Table 2: Comparison of the observed CF7 test results with reported characteristics of conventional water-based EV firefighting approaches

Parameter	CF7	Water only (reported values [7])
Water volume required	1,980 L (incl. 6% CF7)	approx. 2,500 L in a ten-minute attack with two hoses, after which a controlled burn is advised [7]
Total suppression time	6 min 1 s	approx. 30 min in free combustion, rarely more than 1 h [7]
Fire re-ignition	None observed in this test	reported in about 13% of documented cases, most often after the vehicle has been moved [7]

Under the conditions of this test, visible combustion ceased in about one fifth of the average free-burn duration reported in operational guidance, using a water volume comparable to that of a conventional ten-minute attack with two hoses [7]. The observed benefit therefore lies mainly in the shortened duration of the event rather than in the volume of water used. Because no water-only control test was carried out under identical conditions, these differences should be interpreted as indicative rather than as a quantified performance comparison. Recent full-scale experiments have furthermore reported that fires in electric and internal combustion engine vehicles can be comparable in fire growth rate, peak size and duration, and that none of the suppression techniques tested there halted thermal runaway once it had started [18]. The present result should therefore be read as a single operational observation that warrants systematic comparison under controlled conditions. These improvements may have positive implications for firefighter safety and environmental impact. Reduced water use may decrease the volume of potentially contaminated runoff, while shorter suppression times may reduce the duration of firefighter exposure to hazardous combustion products.

The absence of re-ignition during the monitoring period was one of the most operationally significant findings. Under current practice, re-ignition of EV battery fires after apparent extinguishment is a well-documented hazard requiring prolonged standby, repeated interventions, and extended crew exposure in the hazardous zone [6, 18]. The extended cooling effect observed after CF7 application may contribute to reducing the risk of re-ignition by maintaining lower battery temperatures after active suppression. In this test, no re-ignition was observed during the post-test monitoring period.

It should be noted that the present study reports the results of a single operational test conducted on one vehicle with the battery charged to 20% state of charge. The vehicle was positioned on its side and thermal runaway was initiated by mechanical puncture of the battery pack. In addition, no water-only control test was performed under identical conditions, and the post-test monitoring period of several hours is considerably shorter than the ten-day quarantine recommended in European guidance for burned electric vehicles [9], so the absence of re-ignition can only be established for the period actually observed. The vehicle was also not moved after the intervention, whereas re-ignition is reported to occur most frequently once a vehicle or battery has been displaced [7]. These factors limit the generalisability of the findings. Further testing at higher battery states of charge, in standard upright vehicle orientations, and under comparable control conditions is therefore recommended to provide additional validation across a wider range of incident scenarios.

6. FIREFIGHTER SAFETY IMPLICATIONS

Shortening the duration of active thermal runaway may reduce cumulative firefighter exposure, provided that other exposure conditions are comparable. Hazardous gases such as hydrogen fluoride (IDLH: 30 ppm) and carbon monoxide (IDLH: 1,200 ppm) may be released during lithium-ion battery thermal runaway, making reduced time in the hazard zone potentially beneficial for firefighter safety [11, 12].

The test findings suggest the following potential safety benefits for firefighting personnel:

- Reduced thermal exposure: shorter active fire duration may reduce the duration of radiant heat exposure and the risk of secondary ignition in the vicinity of the vehicle.
- Lower cumulative toxic gas load: earlier termination may limit the total volume of CO, HF, flammable hydrocarbons, and respirable particulates released at the incident site.
- Reduced risk of re-ignition: the prolonged cooling effect may reduce the likelihood of delayed re-ignition and the need for extended standby deployment or repeat interventions.
- Shorter time in the hazard zone: reduced suppression time may decrease firefighter exposure to radiant heat, toxic plume, structural instability, and physical fatigue under breathing apparatus.
- Improved incident predictability: earlier scene stabilisation may reduce the dynamic escalation of hazards and provide incident commanders with greater tactical control.

Beyond the immediate suppression event, the PFAS-free formulation of CF7 avoids occupational exposure to PFAS originating from the extinguishing agent itself, thereby reducing one potential source of repeated PFAS exposure for firefighting personnel. Occupational exposure as a firefighter is classified as carcinogenic to humans (Group 1), and chemicals present in firefighting foams are among the exposures considered in that evaluation [19].

7. CONCLUSION

The operational test conducted in Karlovac on 20 November 2025 showed that, under the specific conditions of the test, the application of Flamblocker CF7 ceased visible combustion and significant gas emission of a lithium-ion battery thermal runaway in a passenger electric vehicle in 6 min 1 s, using 1,980 L of total extinguishing solution containing 6% CF7, with no re-ignition observed during the post-test monitoring period. These findings indicate promising performance under the specific conditions of this operational test and warrant further controlled evaluation.

The core safety benefit is the reduction in exposure time. Thermal runaway fires generate a hazardous combination of extreme heat, flammable gas mixtures, and highly toxic emissions; an agent that shortens event duration may therefore reduce the cumulative risk to first responders. CF7 achieves this while being PFAS-free and aligning with the broader EU regulatory shift away from PFAS-containing firefighting formulations.

Further controlled and repeated testing at higher battery states of charge, with different vehicle types and orientations and, where possible, comparative suppression methods, is recommended before broader operational integration of CF7 into national firefighting protocols is considered.

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Professional paper

FIRE PROTECTION OF ELECTRIC FORKLIFTS AND LITHIUM-ION BATTERY CHARGING STATIONS: FIRE RISKS AND PRACTICAL RECOMMENDATIONS

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Abstract: *The increasing use of electric forklifts powered by lithium-ion batteries has introduced new fire safety challenges in industrial facilities. Although these systems provide environmental and operational benefits, they also present specific risks associated with battery charging, thermal runaway, and the release of toxic gases. This paper analyses the main fire hazards related to electric forklifts and charging stations and reviews current international fire safety recommendations. Based on the identified risks, technical and organisational fire protection measures are proposed, including charging station design, fire detection systems, emergency procedures, and the use of specialized extinguishing agents. The findings highlight the importance of integrating engineering controls, risk assessment, and employee training to improve fire safety in industrial environments.*

Keywords: *electric forklifts, lithium-ion batteries, charging stations, fire protection, thermal runaway*

1. INTRODUCTION

Electric forklifts have become increasingly common in industrial facilities due to their high energy efficiency, low operating costs, and reduced environmental impact. Compared with internal combustion forklifts, electric models produce no direct exhaust emissions and require less maintenance. As a result, many manufacturing and logistics companies are replacing conventional vehicles with electrically powered alternatives [1].

The widespread adoption of lithium-ion batteries has significantly improved forklift performance by reducing charging times and extending battery life. However, these advantages are accompanied by new fire safety challenges. Unlike conventional fuel-related fires, lithium-ion battery incidents may involve thermal runaway, rapid heat release, toxic gas generation, and reignition after apparent extinguishment [2].

Current Croatian legislation, including the Fire Protection Act (NN 92/10, 114/22) and the Occupational Safety Act (NN 71/14, 118/14, 154/14, 94/18, 96/18), establishes general fire protection and occupational safety requirements. However, no dedicated national legislation specifically addressing lithium-ion-powered industrial trucks and their charging stations was identified during the review conducted for this paper. Consequently, organizations often rely on international standards and guidance documents as supplementary references when designing charging facilities and selecting fire protection measures [3] [4].

2. FIRE RISKS ASSOCIATED WITH ELECTRIC FORKLIFTS AND CHARGING STATIONS

2.1. THERMAL RUNAWAY

The most significant fire hazard associated with lithium-ion batteries is thermal runaway. This phenomenon occurs when a battery cell experiences a rapid increase in temperature that initiates a self-sustaining chain reaction. Heat generated inside the battery causes neighbouring cells to become unstable, potentially leading to fire or explosion. During thermal runaway, battery temperatures increase rapidly and hazardous gases such as hydrogen fluoride (HF), carbon monoxide (CO), and flammable vapours may be released, depending on battery chemistry and operating conditions [2].

Unlike conventional fires, lithium-ion battery fires can reignite several hours after apparent extinguishment. This characteristic makes firefighting operations particularly challenging and requires specialized prevention and response strategies.

2.2. MAIN CAUSES OF BATTERY FIRES

Several factors may contribute to battery failure and subsequent fire incidents.

Table 1: Main fire hazards associated with electric forklifts

HAZARD	POTENTIAL CONSEQUENCE
Mechanical battery damage	Internal short circuit
Overcharging	Thermal runaway
Battery management system failure	Cell overheating
Defective charger	Electrical fire
Poor charging station design	Fire spread and delayed response
Inadequate ventilation	Accumulation of hazardous gases

Source: Author's synthesis based on [2] [5] [6].

Mechanical impacts, improper charging procedures, electrical faults, and insufficient maintenance represent the most common causes of battery-related incidents. The probability of fire increases when these factors occur simultaneously [2] [5].

2.3. RISKS IN CHARGING STATIONS

Charging stations are considered critical areas because batteries experience their highest electrical loads during charging. In enclosed spaces, heat accumulation and limited ventilation may increase fire severity [3] [6]. Furthermore, emergency response can be complicated by restricted access and the presence of energized electrical equipment.

Consequently, charging stations should be regarded as dedicated fire-risk zones requiring specific protective measures beyond the minimum legal requirements.

3. INTERNATIONAL STANDARDS, REQUIREMENTS AND GUIDANCE

3.1. NFPA 855 AND ENERGY STORAGE SAFETY

NFPA 855 is one of the most comprehensive international standards addressing fire protection requirements for stationary energy storage systems. Although it is not specifically intended for lithium-ion-powered industrial trucks or their charging stations, several principles related to fire separation, ventilation, thermal runaway management, fire detection, and fire suppression may provide useful supplementary guidance when assessing fire protection measures for lithium-ion charging installations. Key recommendations include fire-resistant construction, adequate ventilation, early fire detection systems, and automatic fire suppression measures aimed at limiting fire development and reducing the consequences of thermal runaway events [3].

3.2. OSHA REQUIREMENTS FOR BATTERY CHARGING

OSHA requirements applicable to battery charging are primarily intended for occupational safety and employee protection in charging areas within the United States. OSHA provisions such as 29 CFR 1910.178 and 29 CFR 1926.441 focus on employee safety and accident prevention during charging operations. Charging areas should be adequately ventilated, protected from ignition sources, and equipped with emergency response equipment. Regular inspection of batteries, chargers, connectors, and electrical installations is also recommended. Employee training plays a crucial role in reducing operational errors and improving emergency preparedness [1] [6].. Although these requirements were primarily developed for conventional battery systems, particularly lead-acid batteries, several principles related to workplace safety, equipment inspection, charging-station management, and emergency preparedness may also be relevant when assessing lithium-ion battery charging operations.

3.3. RC59 RECOMMENDATIONS

RC59 provides practical guidance for reducing fire risks associated with electric vehicle charging installations and battery charging activities. Although RC59 is not specifically intended for forklift-truck charging systems, several recommendations related to charging-station location, separation from combustible materials, emergency planning, and access for firefighting operations may provide useful supplementary guidance when assessing charging facilities for lithium-ion-powered industrial trucks. Emphasis is placed on fire risk assessment, management procedures, and emergency preparedness aimed at reducing the consequences of battery-related incidents [4].

4. PRACTICAL FIRE PROTECTION MEASURES FOR INDUSTRIAL FACILITIES

4.1. TECHNICAL FIRE PROTECTION MEASURES

Based on the fire hazards associated with lithium-ion battery charging, dedicated charging areas may be considered as a risk-reduction measure, particularly in facilities with larger forklift fleets or elevated fire loads. Where reasonably practicable, charging stations should be separated from production and storage operations and supported by adequate ventilation, emergency shutdown equipment, and access for emergency responders. Charging equipment may also be protected from accidental mechanical damage through physical barriers or protective bollards [1] [3] [4].

Mechanical ventilation may improve safety by facilitating the removal of heat and potentially hazardous gases released during battery degradation. Clearly marked emergency shutdown devices may support rapid electrical isolation and improve emergency response effectiveness during battery-related incidents [3] [7].

Electrical installations and charging equipment should comply with applicable industrial truck electrical safety requirements in order to minimize the risk of electrical faults and overheating [8].

4.2. EARLY FIRE DETECTION SYSTEMS

Early detection is essential because lithium-ion battery failures often develop internally before visible flames appear. Conventional smoke detectors provide basic fire detection, while heat detectors can identify abnormal temperature increases. Gas detection systems may be used to identify hazardous gases released during battery degradation [9]. For enclosed charging facilities, aspirating smoke detection systems such as VESDA may provide earlier warning of developing fire conditions than conventional smoke detectors by continuously sampling air and detecting very low concentrations of combustion products. Consequently, such systems are frequently considered for applications where early fire detection is regarded as particularly important [10].

4.3. F-500 EA AS A FIREFIGHTING SOLUTION

Lithium-ion battery fires present significant challenges for conventional extinguishing agents. Dry powder extinguishers may suppress visible flames but generally do not stop ongoing chemical reactions within battery cells. Similarly, carbon dioxide systems may reduce oxygen concentration and temporarily control fire development, but they are not specifically intended to prevent battery reignition. Conventional foam agents may also have limited effectiveness during thermal runaway events due to the nature of lithium-ion battery failures [2].

F-500 Encapsulator Agent (F-500 EA) is a firefighting additive intended for a variety of industrial fire hazards, including lithium-ion battery incidents. According to manufacturer documentation, the agent combines rapid cooling, encapsulation of combustible particles, and mitigation of thermal runaway propagation. Independent testing conducted by Kiwa Nederland BV reported that portable F-500 extinguishers were capable of achieving fire suppression and fire control when applied to lithium-ion battery fire scenarios under controlled test conditions. Reported outcomes included a reduction in fire intensity and battery temperature, as well as improved control of fire development during testing [11][12].

Available test reports cited in the author's graduate thesis indicated favourable results for F-500 extinguishers when compared with conventional powder and foam extinguishers in lithium-ion battery fire scenarios. Reported outcomes included battery cooling, reduced fire intensity, and improved post-fire stability of the tested battery systems. However, additional independent research would be beneficial to further evaluate performance under different battery chemistries, capacities, and operating conditions [11][12].

Therefore, F-500 EA extinguishers may be considered a supplementary firefighting measure for facilities operating lithium-ion-powered forklifts and charging stations, particularly where additional protection against battery-related fires is desired [11][12].

4.4. ORGANISATIONAL FIRE PROTECTION MEASURES

Technical measures alone cannot eliminate all risks. Employees should receive regular training on battery hazards, charging procedures, emergency shutdown operations, and evacuation protocols. Regular inspections should verify battery condition, charger functionality, cable integrity, and charging station housekeeping practices [1] [6].

In addition, organizations should conduct periodic lithium-ion-specific risk assessments and develop emergency response plans that address battery fires, communication procedures, and coordination with local fire services [4].

5. DISCUSSION

The growing use of lithium-ion-powered forklifts has created fire safety challenges that are not fully addressed by existing national regulations. Consequently, industrial facilities increasingly rely on internationally recognized standards and recommendations to establish appropriate safety measures.

Table 2: Comparison of existing and recommended practices

EXISTING PRACTICE	RECOMMENDED IMPROVEMENT
Basic charging area	Dedicated charging zone
Portable extinguishers only	Specialized battery fire protection
Standard smoke detection	Early-warning detection systems
General risk assessment	Lithium-ion-specific assessment
Periodic training	Scenario-based emergency training

Source: Author’s synthesis based on [3] [4] [9] [11].

Based on the author’s professional experience gained during the implementation and operation of electric forklift charging stations at Wienerberger Hrvatska, the combination of technical fire protection systems and organizational controls appeared to contribute to improved fire safety performance.

6. CONCLUSION

The increasing use of lithium-ion-powered electric forklifts has introduced new fire protection challenges in industrial facilities. Thermal runaway, toxic gas release, and battery reignition represent hazards that differ significantly from conventional industrial fire risks.

Current national regulations provide limited guidance regarding lithium-ion battery charging stations, highlighting the importance of applying internationally recognized standards and industry recommendations.

The analysis presented in this paper indicates that effective protection requires a combination of technical and organizational fire protection measures. Early fire detection, dedicated charging station design, employee training, emergency planning, and specialized extinguishing solutions such as F-500 EA may help reduce the probability and consequences of battery-related fires.

Future regulatory developments should establish clearer requirements for lithium-ion battery charging facilities in order to support the safe implementation of electric forklift technology throughout industry.

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Professional paper

ERP SYSTEM IMPLEMENTATION – AN EXAMPLE OF A MANUFACTURING COMPANY

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Abstract: *ERP (Enterprise Resource Planning) is a set of software management tools that provide sophisticated integration between company departments (e.g., sales, marketing, production, operations, logistics, procurement, finance, human resource management) allowing employees to work more efficiently and productively while reducing costs and inventory, and laying the foundation for a more effective business environment. This paper aims to demonstrate the organization of an ERP system in a manufacturing company, covering the entire process from customer inquiry to invoicing, and everything that happens in between. It also discusses the benefits, challenges and key considerations involved in ERP implementation to ensure that the reports generated are accurate and relevant.*

Keywords: *ERP, ERP system implementation, manufacturing company*

1. INTRODUCTION

Enterprise Resource Planning (ERP) systems are integrated software solutions designed to support and coordinate core business functions within an organization [1]. ERP systems provide integration between business departments (e.g. sales, procurement, production, logistics, finance, HRM) within a unified information system, enabling efficient data flow, improved operational control, and enhanced decision-making capabilities [2]. The implementation of ERP systems is a strategic initiative involving a redesign and alignment of business processes ensuring relevant, timely and precise information flow and exchange across business departments and functional areas [3]. Such an integrated approach reduces manual data handling, minimizes errors, and improves the reliability and timeliness of business information [4]. When properly implemented, these systems support end-to-end process integration [5], starting from the initial customer inquiry, through order processing, production, procurement, warehousing, to final invoicing. However, ERP implementation presents challenges such as process standardization, data quality management, user adoption and organizational change management [6].

2. ERP-Supported Business Processes in a Manufacturing Company

ERP should not be viewed merely as a collection of software modules. In manufacturing companies, its primary value lies in integrating business processes (customer inquiry, procurement, production, inventory management, invoicing) into a unified information environment that supports efficient operations and informed decision-making. The effective integration of business processes within an ERP system relies on the availability of accurate, consistent, and standardized master data.

2.1. Master Data: Foundation of Process Integration

Unlike transactional data, which are generated during daily business operations, master data represent relatively stable information that is shared across multiple organizational functions and serves as the foundation for all subsequent business activities [7]. The quality of master data directly influences the reliability of business processes, reporting, and managerial decision-making [8].

In a manufacturing environment, the most important master data include items, customer, suppliers, warehouses, units of measure, tax rules, and other reference data required to execute operational processes. These data are entered once and subsequently reused throughout the ERP system, ensuring that all departments operate using the same information. As a result, sales, procurement, production, warehousing, and accounting activities remain synchronized, while unnecessary duplication of data entry and inconsistencies between departments are minimized.

The integrated nature of ERP systems enables each business transaction to reference the same master data records regardless of the business function in which it originates [9]. E.g. and item defined within the master data can be quoted to a customer, purchased from a supplier, consumed during production, stored in a warehouse, and ultimately included on a customer invoice without requiring repeated data entry. This unified data structure improves data integrity, enhances process traceability, and supports real-time information exchange across the organization.

Building upon this common data foundation, the ERP system integrates the key business processes of a manufacturing company, including sales, procurement, production, warehouse management, workstation-level data entry, and reporting. The relationship between master data and the main ERP-supported functional areas is shown in Figure 1.

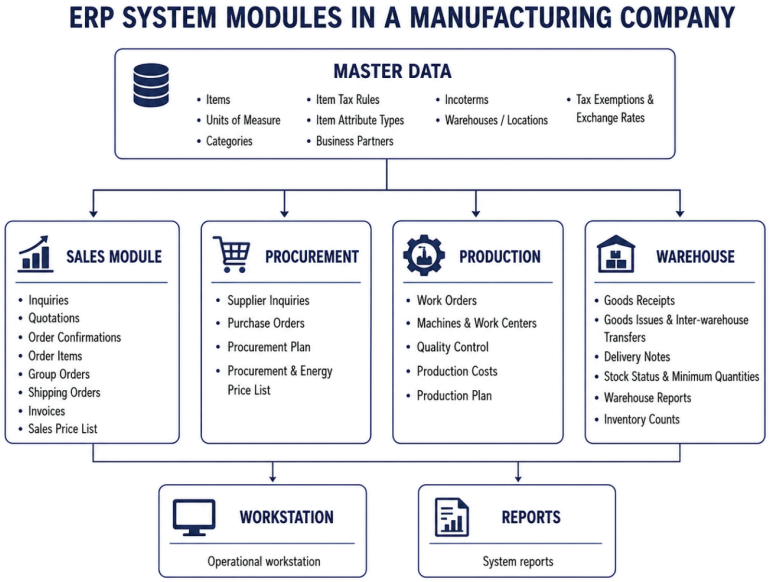


Figure 1: ERP system modules and master data integration in a manufacturing company

The following sections describe how ERP systems integrate the key business processes of a manufacturing company, beginning with customer order fulfilment, continuing through procurement and production activities, and concluding with inventory management and invoicing.

2.2. Oder-to-Cash Process: Sales

The Order-to-Cash (O2C) process represents one of the core business processes supported by ERP systems, integrating activities from the initial customer inquiry to the final invoice [1, 2]. Rater then treating sales, production, warehousing, and accounting as isolated functions, ERP enables these activities to operate within a unified information environment [3]. Customer inquiries are converted into quotations, which, upon acceptance, generate sales orders containing all relevant customer, product, pricing, and delivery information. The sales order subsequently initiates downstream activities, including production planning for make-to-order products or warehouse reservation for finished goods [7, 8].

As production progresses or inventory becomes available, delivery documents are generated and inventory records are updated automatically. Once goods are dispatched, the ERP system creates the corresponding customer invoice using information already captured during previous process stages, eliminating redundant data entry and reducing the possibility of inconsistencies [8]. Throughout the process, all departments access the same transactional information in real time, improving coordination, delivery performance, and customer service while providing complete traceability from customer inquiry to payment [4, 7].

2.3. Procure-to-Pay Process: Procurement

The Procure-to-Pay (P2P) process integrates purchasing activities with inventory management, production, and financial accounting [10, 11]. Material requirements are generated based on production plans, inventory levels, or customer demand [12]. ERP systems support the preparation of supplier inquiries and purchase orders while maintaining centralized supplier information and purchasing conditions [10, 11].

Upon receipt of materials, warehouse inventory is updated automatically, and the received quantities become immediately available for production planning and inventory control [4, 15]. The corresponding purchasing documents provide the basis for supplier invoice verification and financial posting, ensuring consistency between procurement, inventory, and accounting records [4, 10]. By integrating these activities within a single system, ERP improves procurement transparency, shortens purchasing cycles, and reduces the likelihood of stock shortages or duplicate purchases [4, 17].

2.4. Value creation process: Production

Production planning and execution constitute the central component of ERP implementation in manufacturing companies [11, 14]. Based on confirmed customer orders or production forecasts, the ERP system generates production plans that determine material requirements, machine allocation, work centers, and production schedules [11, 13]. Work orders define the operations required to manufacture products while coordinating the availability of materials, equipment, and personnel [10, 11].

During production, material consumption, labor activities, and production progress are recorded directly within the ERP system [14]. Quality inspections can be integrated into individual production stages, ensuring that products comply with predefined quality requirements before progressing to subsequent operations [13, 14]. Upon completion, finished products are automatically transferred to inventory while production costs are calculated using recorded material consumption, labor and machine utilization [10, 14]. This integration provides management with real time visibility into production performance and resource utilization, facilitating more effective production planning and continuous process improvement [4, 14].

2.5. Inventory flow control: Warehouse

Inventory management connects procurement, production, and sales by maintaining accurate information on material availability and product movement throughout the organization [4, 15]. Every inventory transaction – including goods receipt, materials issue, warehouse transfer, production consumption, and customer shipment - is recorded immediately withing the ERP system, ensuring that inventory balances remain current across all business functions [15].

Real-time inventory visibility supports production scheduling, procurement planning, and customer order fulfilment while reducing excess inventory and minimizing stock shortages [4]. Warehouse operations such as purchasing, production, and sales transactions, providing complete traceability of material movements [16]. The resulting information supports operational decision-making and enables managers to monitor inventory performance through standardized ERP reports and key performance indcators [4, 16].

2.6. Workstation

The workstation represents the operational interface within the ERP system where production and logistics activities are executed and recorded in real time. It serves as the point of interaction between users and the ERP system, enabling the direct recording of production operations, material consumption, machine usage, and task completion [10, 11.]. Through workstation terminals, employees confirm production steps and report progress directly into the system, ensuring real-time synchronization between physical operations and digital records [15]. This supports accurate tracking of work orders, resource usage, and operational performance while reducing delays in

data capture [4, 15]. By integrating workstation-level data entry into the ERP system, organizations achieve real-time synchronization between physical operations and digital records, which supports production monitoring, cost tracking, and operational control [12].

2.7. Reports

Reporting represents the analytical layer or ERP systems, transforming transactional and operational data into structured information for managerial decision-making [4, 12.]. ERP reporting tools consolidate data from sales, procurement, production, and inventory processes to provide real-time visibility of business performance [12, 16].

Standardized reports include production performance, inventory levels, procurement status, sales, analysis, and financial summaries, enabling monitoring of key performance indicators and operational efficiency [4, 16]. The integration of reporting functions within the ERP system ensures that all reports are based on a single consistent data source, eliminating discrepancies between departments [12].

Advanced reporting capabilities support decision-making by enabling managers to analyze historical and real-time data across business processes [4, 16].

3. CONCLUSION

Rather than focusing on ERP as a set of isolate modules, the focus of this paper was on continuous process flows starting from customer order initiation, through procurement and production, ending with inventory management and reporting. This approach highlight that the primary value of ERP systems lies in the integration and synchronization of business processes across organizational functions.

Master data represents the fundamental prerequisite for successful process integration, as they ensure consistency of information across all operational areas. Process execution in ERP environments depends heavily on the quality and discipline of data entry during transactional activities. Inconsistent of incomplete data can significantly reduce the effectiveness of otherwise well-designed ERP processes. At the same time, the highest operational benefit is achieved through real-time data availability, which enables improved coordination between departments, reduced delays in information flow, and increased transparency of operations.

ERP contribute to improved operational control in manufacturing environments by linking production, logistics, procurement, and financial processes into a single coherent system. This integration supports more accurate planning of materials and capacity, reduces the risk of stock imbalances, and improves traceability of materials and products throughout the production cycle. Although ERP implementation requires organizational alignment and disciplined process execution, the resulting benefits include higher process efficiency, improved decision-making quality, and better overall control of business operations.

In the context of manufacturing companies, ERP systems therefore represent not only an IT solution, but also a process integration framework that supports operational reliability and structured information flow. Their effectiveness ultimately depends on the alignment between system design, organizational processes, and user adoption.

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Original scientific paper

PROTECTION OF MINORS AT WORK IN THE LEGISLATION OF BOSNIA AND HERZEGOVINA

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Abstract: *Minor employees represent a particularly protected category of employees in modern legislation. Their protection at work represents an important segment of the labor and social legislation of Bosnia and Herzegovina, with the aim of preserving the health, safety and proper development of young people who are employed.*

The paper pays special attention to defining the concept of minor employeess, the conditions for establishing an employment relationship, including the minimum age, the mandatory consent of parents or guardians, as well as a medical examination confirming their working capacity. The paper is also dedicated to certain restrictions regarding working hours, the ban on night work, overtime work and work in jobs that pose an increased risk to the health and safety of minor employees. The paper analyzes the current legal regulations at the state level of Bosnia and Herzegovina, the entities and the Brcko District of Bosnia and Herzegovina, with special emphasis on compliance with international standards in this area.

The work indicates the obligation of employers to ensure special measures of protection at work for minor employeess, including adjustment of working conditions, safety education and supervision of their work. Mechanisms of inspection supervision and sanctions for violation of legal provisions are also analyzed.

Keywords: *minor employees, occupational safety, labor legislation, Bosnia and Herzegovina*

1. INTRODUCTION

Occupational safety and health represents are one of the fundamental rights of employees and an important component of modern labour legislation. Special importance is attached to the protection of young employees, considering their physical and psychological immaturity, of work experience, and increased vulnerability to risks that may arise in the workplace. For these reasons, minors constitute a specially protected category of employees to whom legislation pays particular attention through limitations on working hours, the prohibition of certain types of work, and the mandatory implementation of specific occupational health and safety measures.

In modern working conditions, there is an increasing need to balance employers' economic interests with the protection of the health and safety of young people entering the labour market for the first time. Young worke employees often lack sufficient experience, knowledge and awareness of workplace hazards, making them more vulnerable to occupational injuries, work-related illnesses, and other harmful consequences. Therefore, the legislation of International Labour Organization (ILO) and the European Union (EU), establish minimum standards for the protection of young worke employees that states are required to incorporate into their national legislation.

In Bosnia and Herzegovina (B&H), the protection of young employees is regulated through various laws and bylaws at the state, entity, and Brcko District B&H levels. In the continuation of this work, it will bi considered the legislation that is prescribed, especially labour laws and occupational safety and health legislation.

2. CONCEPT AND LEGAL STATUS OF YOUNG EMPLOYEES

Young employees constitute a special category of employees who, due to their age and stage of physical and psychological development, require additional legal and health protection within the employment relationship. The protection of young employees at work is based on the principle of safeguarding their life, health, safety, moral development, and education. So, modern labour legislation establishes specific conditions under which minors may enter into employment, as well as restrictions regarding the types of work they may perform and special privileges concerning the exercise of certain employment rights.

According to the legislation of B&H, a young worker (minor) is a person who has not reached the age of 18. However, certain forms of employment are permitted for persons over the age of 15, provided that the conditions prescribed by law are fulfilled.

The legal status of young employees differs from that of adult employees precisely because of the need for their special protection. Therefore, the law prescribes additional conditions for entering into an employment relationship, such as the minor's voluntary consent to work, the requirement that the type of work and tasks performed do not adversely affect their physical and psychological development or interfere with their compulsory and regular education, as well as the requirement that they are medically fit for work and employed with the consent and under the supervision of their parent or legal guardian.[1]

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International standards play a significant role in defining the protection of young employees, particularly the conventions of the ILO. Of special importance are the Convention No. 138 concerning the Minimum Age for Admission to Employment[2] Work and Convention No. 182 concerning the Prohibition and Immediate Action for the Elimination of the Worst Forms of Child Labour[3]. In addition to international conventions, an important source of protection for young employees is provided by EU directives, particularly Directive 94/33/EC on the Protection of Young People at Work[4].

3. LEGAL FRAMEWORK FOR THE PROTECTION OF YOUNG EMPLOYEES IN BOSNIA AND HERZEGOVINA

The legal framework governing the protection of young employees in B&H is based on domestic legislation founded on international standards that regulate the fields of labour, occupational safety and health, and the protection of children and young persons.

In the Federation of B&H, the protection of young employees is primarily regulated by the Labour Law of the Federation of B&H [5] and the Occupational Safety and Health Law of the Federation of B&H [6]. These regulations define the minimum age for employment, the conditions under which minors may enter into an employment relationship, restrictions on night work and overtime work, as well as prohibitions on performing jobs that pose an increased risk to health and safety. Particular importance is attached to the provisions concerning mandatory medical examinations, risk assessments, and the implementation of special occupational safety and health measures for young employees.

In Republika Srpska (RS), the protection of young employees is regulated by the Labour Law of RS[7] and the Occupational Safety and Health Law of RS[8]. The regulations contain provisions similar to those in the Federation of B&H, including limitations on working hours, prohibitions on hazardous work, and the employer's obligation to ensure safe working conditions for minors. The law also defines the responsibilities of labour inspection authorities in monitoring and enforcing the implementation of measures for the protection of young employees.

In the Brcko District of B&H, the protection of young employees is regulated by the Labour Law of the Brcko District of B&H [9] and other subordinate legislation in the field of occupational safety and health. These regulations also prescribe specific conditions for the employment of minors, prohibit engagement in hazardous work and require the implementation of preventive safety and health measures.

[2] Convention No. 138 concerning the Minimum Age for Admission to Employment: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://mladiradnici.me/wp-content/uploads/2018/11/Konvencija-MOR-br.-138-o-minimalnim-godinama-za-zasnivanje-radnog-odnosa-1973..pdf (13.05.2026.).

[3] Convention No. 182 concerning the Prohibition and Immediate Action for the Elimination of the Worst Forms of Child Labour: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.upfbih.ba/uimages/dokumenti/C18220Konvencija20o20najgorim20oblicima20djeC-48Dijeg20rada2C201999.pdf (13.05.2026.).

[4] Directive 94/33/EC on the Protection of Young People at Work: https://www.radniodnosi.hr/33/direktiva-vijeca-europske-unije-o-zastiti-mladih-ljudi-na-radu-uniqueidmRRWSbk196E4DjKFq6pChMz_oMD_T6f2LQWU_8lp1W_qfNrr_tD4hg/32/trazi/?ns=267 (13.05.2026.).

[5] Labour Law of the Federation of B&H, OG of F B&H, No. 26/16, 89/18, 44/22 and 39/24.

[6] Occupational Safety and Health Law of the Federation of B&H, OG of F B&H, No. 79/20.

[7] Labour Law of RS, OG of RS, No. 1/2016, 66/18, 91/2021 – Constitutional Court Decision, 119/21, 112/23, 39/24 and 28/26 – Constitutional Court Decision.

[8] Occupational Safety and Health Law of RS, OG of RS, No. 1/08 and 13/10.

[9] Labour Law of the Brcko District of B&H, OG of Brcko District B&H, No. 12/2025 – consolidated text.

3.1. Legal Conditions for the Employment of Minors in Bosnia and Herzegovina

The lawful employment of minors is explicitly regulated by labour legislation in B&H. All three legislators (the entities and the Brcko District of B&H) treat minors as a specially protected category of employees. Accordingly, the legislator (referring primarily to the labour legislation of the Federation of B&H, while similar provisions are contained in the labour legislation of RS and the Brcko District of B&H) has prescribed that a person between 15 and 18 years of age, i.e., a minor, may enter into an employment contract and be employed only with the consent of a legal representative and provided that he or she obtains a medical certificate from an authorized physician or a competent healthcare institution confirming general fitness for work.[10] This provision of the Labour Law of the Federation of B&H corresponds to the previously mentioned conditions for the employment of a minor, ensuring that such employment is carried out under the supervision of a parent, guardian, or another competent person, with the aim of protecting the young worker from potentially harmful effects of work and the working environment on his or her health, safety, and development.

Also, the legislator has reduced the duration of full-time working hours for young employees. Accordingly, the full-time working week for minors must not exceed 35 hours[11], considering that a 40-hour working week, which is the standard for other employees, could be burdensome and potentially harmful to a young worker. In addition, such a workload might not leave sufficient time for the minor's other obligations, particularly those related to education, which should not be neglected due to employment.

3.2. Protective Provisions of Labour Legislation for Young Employees

As young employees constitute a specially protected category of employees, certain provisions of labour legislation place them in a particularly privileged position. Specifically, a young worker may not be required to work overtime,[12] nor may he or she work under a redistribution of working hours, except where the young worker has given written consent to such work.[13]

The legislator has also prohibited night work for young employees. As an exception, minors may be temporarily exempted from the prohibition of night work in cases of accidents, force majeure, or where necessary to protect the interests of the Federation of B&H, subject to the approval of the cantonal labour inspectorat.[14] This prohibition is fully justified when it is taken into account that night work has a specific impact on the physical and psychological condition and overall health of employees, as well as on the organization and rhythm of their daily activities and responsibilities. Supporting this view is the fact that even adult employees engaged in night work generally enjoy certain benefits intended to mitigate or prevent the harmful effects that such work may cause. So, these employees are often entitled to more frequent medical examinations, special financial compensation, longer annual leave, extended service credit for pension purposes, and other similar benefits, which can hardly be regarded as privileges but rather as compensation for the potential harm that night work may have on employees' health.[15]

[10] Article 20 paragraph 2 of Labour Law of the Federation of B&H.
[11] Article 36 paragraph 3 of Labour Law of the Federation of B&H.
[12] Article 38 paragraph 3 of Labour Law of the Federation of B&H.
[13] Article 39 paragraph 5 of Labour Law of the Federation of B&H.
[14] Article 45 of Labour Law of the Federation of B&H.
[15] Beslagic, J.: Prekrsajna odgovornost poslodavca zbog ogranicavanja prava maloljetnog radnika, Zbornik radova sa 17. Medunarodne konferencije „Djeca i maloljetnici u kaznenom pravu", Istrazivacki centar Banja Luka, Narodna skupstina Republike Srpske, Ministarstvo pravde Republike Srpske, Udruzenje pravnika Republike Srpske, Srpsko udruzenje za krivicnopravnu teoriju i praksu; ISBN 978-99997-969-4-1, Banja Luka, 2026., 417.

Also, young worker is entitled to annual leave of at least 24 working days,[16] whereas other employees are entitled to a minimum of 20 working days. As annual leave serves, the law recognizes the specific needs of minors as a particularly vulnerable category of employees and imposes an obligation on employers to ensure the exercise of this right.

The legislator has also prescribed that minors may not be employed in particularly strenuous physical work, underground or underwater work, or in any other that could associated risks, adversely affect the minor's life, health, development, or moral well-being, taking into account the minor's physical and psychological characteristics.[17] In the case of this legal provision, the legislator has already clarified the reasons for introducing such a prohibition through a specific legal norm.

Labour legislation provide obligation to prevent situations that could be harmful to young employees and to protect their health and physical and psychological development, as well as to ensure the timely detection of any changes in their health condition. So, young employees are entitled to a medical examination at least once every two years, with the costs of such examinations being borne by the employer.[18]

4. OCCUPATIONAL SAFETY AND HEALTH PROTECTION OF YOUNG EMPLOYEES

The occupational safety and health protection of young employees represents one of the most important aspects of labour and social legislation, considering that young persons, due to their lack of experience, incomplete physical development, and insufficient awareness of workplace hazards, constitute a particularly vulnerable category of employees. The objective of protecting young employees is to prevent occupational injuries, work-related diseases, and other harmful consequences that may negatively affect their health, safety, and proper development.

Occupational safety and health legislation has devoted special attention to the protection of groups of employees who are particularly vulnerable to workplace risks. Accordingly, employers are required to organize workplaces in a manner that takes into account the presence of employees who are sensitive to specific risks, including pregnant women, women who have recently given birth or are breastfeeding, minors, persons with disabilities, and employees with reduced working capacity as defined by pension and disability insurance regulations[19]. This provision imposes a specific obligation on employers to take all necessary measures to ensure a safe working environment for vulnerable groups of employees, including minors, and to reduce potential risks to their life and health to the lowest possible level. Furthermore, the legislator has established restrictions on the employment of particularly vulnerable groups of employees in certain types of work. Accordingly, minors are prohibited from performing jobs that may endanger their health and development. Through this provision, the legislator recognizes that certain workplaces involve an increased risk to the health and development of young employees and therefore completely prohibits the employment of minors in such positions. Consequently, this provision may be regarded as a preventive measure aimed at protecting young employees from exposure to hazardous working conditions.

[16] Article 40 paragraph 2 of Labour Law of the Federation of B&H.
[17] Article 57 paragraph 1 of Labour Law of the Federation of B&H.
[18] Article 58 of Labour Law of the Federation of B&H.
[19] Article 69 of Occupational Safety and Health Law of the Federation of B&H.

Based on the foregoing, it can be concluded that the legal framework of B&H provides a significant level of protection for young employees through domestic legislation and international standards. However, the effectiveness of such protection depends on the consistent implementation of legal provisions, preventive action, and the cooperation of all competent institutions and employers.

5. INSPECTION OVERSIGHT OF THE IMPLEMENTATION OF OCCUPATIONAL SAFETY AND HEALTH MEASURES FOR YOUNG EMPLOYEES

An important aspect of the occupational safety and health protection of young employees is inspection oversight. Labour inspectorates are authorized to monitor the implementation of legal provisions relating to the protection of young employees, verify working conditions, working hours, medical examinations, and other protective measures. In cases where irregularities are identified, inspection authorities may issue warnings, impose financial penalties, or take other measures against employers.[20]

Although the legislation of B&H largely incorporates the fundamental standards for the protection of young employees, certain challenges remain in the practical implementation of these regulations. The most common issues relate to insufficient supervision of the work performed by minors, inadequate risk assessments, insufficient education and awareness of employers and employees, as well as the occurrence of undeclared employment of young persons without adequate legal protection. Therefore, it is necessary to continuously improve the legislative framework, strengthen inspection oversight, and raise awareness regarding the protection of the health and safety of young employees.

Effective protection of young employees cannot be achieved without adequate inspection oversight and clearly defined employer responsibilities. Inspection oversight represents an important mechanism for monitoring compliance with labour and occupational safety and health regulations, aimed at preventing abuses, illegal employment, and threats to the health and safety of minors in the workplace. Supervision of the implementation of regulations governing the employment of minors is carried out by the competent labour inspectorates in the Federation of B&H, RS and the Brcko District of B&H. Labour inspectors are authorized to monitor the legality of the employment of minors, verify the existence of the required documentation, assess compliance with working conditions, oversee the implementation of occupational safety and health measures, and ensure adherence to prohibitions relating to night work, overtime work, and the performance of hazardous tasks.

During inspection oversight, particular attention is paid to verifying whether young employees have the required consent of their parent or legal guardian, whether a pre-employment medical examination has been conducted, and whether the employer possesses a documented risk assessment for the workplaces where minors are employed. Inspectors also review records of working hours, training for safe and healthy work, the use of personal protective equipment, and the implementation of other preventive occupational safety and health measures.

In cases where irregularities are identified, labour inspectors are authorized to order the correction of deficiencies, prohibit the employment of minors in certain jobs, or impose misdemeanor sanctions against the employer. The legislation provides for financial penalties for employers who engage

[20] Dedic, S., Gradascevic-Sijercic, J.: Radno pravo, Pravni fakultet Univerziteta u Sarajevu, Sarajevo 2005., 457-459.

minors contrary to legal provisions, fail to implement occupational safety and health measures, or allow minors to perform work that poses a risk to their health and safety.[21]

In addition to their enforcement role, inspection authorities also perform a preventive function. Through advisory activities, educational programs, and preventive inspections, they seek to raise employers' awareness of the importance of protecting young employees and the need to comply with legal requirements. Preventive action is particularly important in sectors where there is an increased risk of occupational injuries and where young persons may be engaged in work that is not appropriate for their age and capabilities.

In practice, certain problems continue to occur, particularly in the area of informal employment and insufficient oversight of specific sectors. Minors are sometimes engaged without employment contracts, without adequate protection, and without the implementation of the prescribed occupational safety and health measures. Such practices pose a serious risk to the health and safety of young persons and highlight the need for stronger inspection oversight and stricter enforcement of legal sanctions.

6. CHALLENGES AND OPPORTUNITIES FOR IMPROVING THE PROTECTION OF YOUNG EMPLOYEES

Although the legislation of B&H prescribes a significant number of measures for the protection of young employees, numerous challenges remain in practice that hinder the consistent implementation of legal provisions. These issues most commonly relate to insufficient monitoring of compliance with regulations, a lack of awareness among employers and young employees regarding their rights and obligations, and the prevalence of undeclared employment, where young persons work without adequate legal and health protection. One of the greatest challenges is the insufficient awareness among employers of the importance of protecting young employees.

In certain cases, minors are engaged in work that is not suited to their physical and psychological capacities, without an adequate risk assessment and without the implementation of specific occupational safety and health measures. A particular concern is the employment of young persons in sectors with an increased risk of occupational injuries, such as construction, manufacturing, hospitality, and agriculture. In addition, a number of minors work without a formal employment contract and without being registered with the competent authorities, thereby being deprived of basic legal and health protection. Such forms of informal employment increase the likelihood of exploitation, excessive workloads, and work in unsafe conditions. In these cases, pre-employment medical examinations, occupational safety and health training, and the use of appropriate personal protective equipment are often absent. Another challenge is the insufficient education of young employees in the field of occupational safety and health. Young employees are often not adequately informed about workplace hazards and risks, nor do they possess a sufficiently developed awareness of the importance of implementing protective measures. As a result, there is an increased risk of occupational injuries, particularly in hazardous jobs or demanding working environments.

Therefore, a specific form of control and supervision of the work performed by minors is labour inspection oversight, with labour inspectors having at their disposal a wide range of measures that may be used to ensure that the employment of minors remains within the legal framework.

[21] Article 159-165 of Labour Law of the Federation of B&H.

An important challenge is also the limited capacity of inspection authorities to conduct continuous monitoring of compliance with legal requirements. The insufficient number of labour inspectors and limited resources hinder the effective supervision of the employment of minors, particularly in small enterprises and sectors where informal employment is prevalent. As a result, certain irregularities remain undetected, or sanctions are not imposed to a sufficient extent.

Strengthening labour inspection oversight represents one of the key measures for improving the system of protection for young employees. It is necessary to increase the number of labour inspectors, enhance coordination among the competent institutions, and ensure more effective sanctioning of employers who violate legal provisions. Particular attention should be directed towards combating undeclared employment and protecting minors employed in the informal sector.

7. CONCLUSION

The occupational safety and health protection of young employees represents an important component of the labour and social legislation of B&H, the primary objective of which is to preserve the health, safety, and proper physical and psychological development of young persons entering employment. Due to their age, limited work experience, and increased vulnerability to workplace hazards and harmful factors, young employees require a special level of legal and health protection. An analysis of the applicable legal regulations leads to the conclusion that B&H possesses a relatively well-developed legal framework governing the conditions for the employment of minors, as well as their rights and limitations in employment. Labour laws and occupational safety and health regulations in the Federation of B&H, RS and the Brcko District of B&H prescribe the minimum age for employment, the mandatory consent of a parent or legal guardian, pre-employment medical examinations, restrictions on night work and overtime work, as well as prohibitions on performing work that poses an increased risk to the health and safety of minors.

Particular importance is attached to international standards, primarily the conventions of the ILO and the directives of the EU which serve as the foundation for the development and improvement of domestic legislation. Their implementation contributes to the harmonization of national regulations with contemporary standards for the protection of the health and safety of young persons at work.

This paper has highlighted the importance of preventive occupational safety and health measures, including risk assessment, the education and training of young employees, the adaptation of working conditions, and continuous supervision of their work. Special responsibility rests with employers, who are required to provide safe and healthy working conditions, as well as with the competent inspection authorities, which monitor compliance with legal provisions and take measures against employers who violate the rights of young employees.

Although appropriate legal regulations are in place, certain problems continue to exist in practice, such as insufficient education and training, the informal employment of minors, their engagement in work that is not suited to their abilities, and insufficiently effective inspection oversight. Therefore, it is necessary to continuously improve the system for the protection of young employees through the strengthening of preventive activities, the education of employers and employees, and the more consistent enforcement of legal sanctions.

It may be concluded that the protection of young employees represents not only a legal obligation but also an important social interest. Creating a safe and healthy working environment for young persons contributes to the protection of their health, their proper development, and their successful integration into the labour market, which in the long term has a positive impact on society as a whole.

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[2] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://mladiradnici.me/wp-content/uploads/2018/11/Konvencija-MOR-br.-138-o-minimalnim-godinama-za-zasnivanje-radnog-odnosa-1973..pdf

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Review article

LEGAL AND NORMATIVE ANALYSIS OF FRAMEWORK DIRECTIVE 89/391/EEC ON OCCUPATIONAL SAFETY AND HEALTH

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Abstract: *The Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work remains the most significant legal instrument of the European Union in the field of occupational safety and health. It is a piece of secondary legislation whose legality is grounded in the provisions of the Single European Act of 1986, and its legitimacy stems from the fact that the same directive emerged as the result of decades-long efforts to redefine the competences of the European legislator regarding the advancement of safety and health systems at work. In this paper, the authors analyze the content of the directive's provisions using normative-legal and dogmatic methods.*

Keywords: *European Union, labor relations, occupational safety and health, Council Directive 89/391/EEC*

1. INTRODUCTION

For a comprehensive understanding of the context in which the Council Directive 89/391/EEC on the introduction of measures to encourage improvements in the safety and health of workers at work (hereinafter: the Framework Directive or FD) was adopted, it is necessary to consider the evolution of European occupational safety and health legislation since the earliest founding treaties. In the initial stages, there was no formal regulatory framework governing this area, and the European legislator's regulatory powers evolved gradually over time, reflecting the incremental development of EU competence in the field of occupational safety and health. In this regard, within the European Coal and Steel Community, research programs were conducted, indicating that issues of occupational safety and health were already recognized within the institutional activities of the Member States [1]. Subsequently, the Treaty of Rome regulated the activities of Member States (hereinafter: MS) in the field of social policy with the aim of achieving common objectives, including the harmonization of working conditions, the improvement of workers' living standards, and the promotion of closer cooperation among MS in areas such as employment, labor law, social security, and occupational safety and health. These provisions laid the foundational principles for

the development of European social policy, with particular emphasis on preventive measures in the area of workplace safety and health. The essence of these provisions lies in the effort to establish a balance between the economic and social objectives of the then European Community, further reinforced by the adoption of the Council Resolution of 21 January 1974 concerning a Social Action Programme and the Council Resolution of 29 June 1978 on an action programme of the European Communities on safety and health at work, both aimed at improving working conditions and worker protection.

With the entry into force of the Single European Act in 1986, clear competencies were established for the European legislator regarding occupational safety and health at the Community level. Its revision amended the Treaty of Rome by introducing Article 118A, which enabled the adoption of directives in this field by a qualified majority, thereby facilitating the establishment of minimum standards for worker protection across the then European Community. On this legal basis, the FD was adopted, institutionalizing occupational health and safety as a core component of European labor law despite the diversity of national legal systems among MS [2]. As the most significant EU legislative act in occupational safety and health, the FD's provisions - still highly relevant today for their objectives, principles, and promotion of a prevention culture - will be presented and analyzed in this paper. This is especially important because directives are binding on MS with regard to the results or objectives to be achieved, but not in terms of the form or method of implementation into national law. MS retain discretionary authority to determine the appropriate legal instrument for transposing the directive, enacting national implementing measures to ensure that domestic legislation aligns with the objectives established by the FD. Such flexibility reflects the specificities of national legal systems and the varying approaches adopted by MS regarding certain European Union (hereinafter: EU) legal concepts. In this context, it becomes evident that specific key provisions of the FD must be interpreted in a manner consistent with its fundamental purpose, as intended at the time of its adoption in 1989, and not in a way that would undermine its overarching objectives.

2. CONTENT, KEY CONCEPTS, AND PRACTICAL APPLICATION OF THE FRAMEWORK DIRECTIVE

FD content covering nineteen articles is structured into four chapters: general provisions, employer obligations, worker obligations, and final provisions, which have served as the basis for establishing national legal frameworks and implementing EU policy in the field of safety and health at work. The first chapter provides an introduction to the objectives and scope of action, while later chapters elaborate specific measures in the workplace through principles of occupational risk prevention, health protection, elimination of accident causes, as well as ensuring information, consultation, and participation of workers and their representatives, along with appropriate training in accordance with national regulations and practices. Simultaneously, the FD does not undermine or preclude national or EU regulations that provide a higher level of protection, as its provisions establish minimum standards that MS are required to incorporate into their national legislation, while retaining the discretionary authority to adopt and implement measures that ensure a higher level of protection for workers.

The FD initially sets out precise definitions of key terms and concepts that are used consistently throughout its provisions, thereby providing a clear legal framework and ensuring uniform interpretation across member states. A worker is any person employed by an employer, including volunteers and trainees, while an employer is defined as a natural or legal person responsible for an

undertaking or establishment. Workers' representatives are individuals with specific responsibilities for safety and health at work, acting in accordance with national law or practice. Since the FD introduces new institutions, such as workers' representatives and safety and health experts, it establishes the foundations of a prevention culture, defined as planned or taken at all stages of work aimed at reducing (or eliminating) occupational risks. This prevention culture is particularly reflected in employer obligations, which encompass all measures for protecting workers' safety and health, including occupational risk prevention, as will be further discussed in the following sections. According to Article 2, the FD applies to all sectors of activity, both public and private, including industrial, agricultural, commercial, administrative, service, educational, cultural, and recreational activities, with certain exceptions such as armed forces, police, and civil protection tasks, where MS retain regulatory sovereignty. Nevertheless, even in these cases, workers' safety and health should be ensured to the greatest extent possible in accordance with the purpose of the FD. The fundamental principles of the FD are intended to be applicable across all sectors of activity, and MS undertake the necessary measures to ensure that employers, workers, and their representatives are fully encompassed by the legal provisions required for its effective implementation, in accordance with Article 4. This ensures a coherent and consistent application of the FD across all relevant workplaces within each MS.

Primary responsibility for ensuring workers' safety and health continues to rest with the employer, who is typically tasked with developing safety plans, organizing training, informing workers, and prioritizing collective over individual protective measures. In the legal systems of EU MS, the employer is the central actor in implementing these obligations, and the adoption of the FD further empowers them to undertake a range of measures to protect workers. Their duties cover all aspects of the work process, applying both preventive and protective measures. The FD is providing detailed regulation of these duties, which will be examined in greater detail in the following sections. The majority of the FD focuses on employer obligations as the entity with the greatest responsibility in implementing safety and health measures at work. Although employers have the primary duty to ensure a safe and healthy working environment, responsibility for safety and health at work is not exclusively theirs. Similar obligations are also borne by individuals involved in the design and manufacture of machinery and tools, while certain responsibilities are delegated to trade unions and workers themselves.

Workers, on the other hand, not only have the right to safe and healthy working conditions but are also obliged to comply with protective regulations and actively cooperate in their implementation [3]. Article 13 defines specific worker obligations, emphasizing the interconnection between rights and duties. Workers are responsible for their own safety and health and that of others affected by their work, following training and instructions, using equipment and protective devices properly, and not tampering with safety mechanisms. In cases of suspected immediate danger, workers are required to notify the employer without delay, thereby ensuring prompt action to mitigate potential risks. They must also actively cooperate with the employer and with appointed safety and health representatives in order to maintain and enhance a safe working environment. The FD thus formalizes prevention - mutual cooperation and active worker participation in workplace safety and health - a key achievement in EU secondary law.

The FD establishes employer obligations that position workers as active participants in ensuring safety and health at work. Workers have the right to timely information on risks and protective measures, access to relevant data, participation in discussions, and the submission of proposals to improve workplace safety, with workers' representatives empowered to request that the employer take appropriate measures. The preventive role of safety and health training is essential to ensure that

workers are adequately prepared to face occupational risks and manage unforeseen or unwanted situations in the workplace. Such training must be specifically tailored to address emerging risks and updated regularly, and it should also include external workers as well as workers' representatives who carry particular responsibilities related to workplace safety and health. The active and coordinated participation of all relevant parties is fundamental to achieving the objectives of the FD, particularly the establishment of a safe and healthy working environment. This collaborative approach further reinforces that prevention constitutes a core principle of the FD and serves as the foundational element of its philosophy in safeguarding workers' safety and health across all MS. It can be properly asserted that the principal objectives at the Union level are aimed at securing safe working conditions and at the elimination or mitigation of potential risks. [4]

3. PREVENTION CULTURE AND ITS CENTRAL ROLE IN THE IMPLEMENTATION OF THE FRAMEWORK DIRECTIVE

The foregoing analysis of the FD's provisions clearly demonstrates that the employer's role is twofold: in addition to implementing preventive measures, the employer is obligated to ensure the adoption of protective measures, all of which are aimed at enhancing the safety and health of workers within the undertaking or establishment. Some of these obligations consist of a compilation of specific preventive and protective actions that the employer is required to implement in the organization of work, including providing first aid, applying countermeasures, etc. Overall, the nature of these obligations is such that the employer cannot evade responsibility under any circumstances if they fail to act in accordance with the FD. Preventive measures are of critical importance, as they not only significantly reduce the risk of adverse consequences to workers' safety and health but also contribute to fostering a culture of prevention within the undertaking.

The FD emphasizes employer obligations in prevention, encompassing measures to avert risks to workers' safety and health. The employer assesses risks when selecting work equipment, handling chemical substances, and organizing the workplace. In doing so, they act in accordance with the general principles of prevention, which include avoiding and evaluating risks, addressing their causes, adapting work processes and equipment, substituting hazardous elements with less dangerous ones, developing a comprehensive prevention policy, prioritizing collective protection over individual measures, and providing clear instructions to workers. Only after the risk assessment, the employer assumes specific responsibilities, while preventive measures and work methods must enhance protection and be integrated into all company activities at all hierarchical levels.

Article 6 of the FD sets out specific employer obligations when assigning tasks to workers, introducing new technologies, and granting workers access to areas with serious risks, with mandatory preventive application of protective measures. The employer must adapt measures to the nature of the work and tasks, and when workers from multiple undertakings operate in the same workplace, employers coordinate their activities and inform workers about the risks. The FD provides a framework for preventive action, establishing the general principles and obligations to be followed by employers. Specific measures - particularly those concerning special protection - are usually further detailed in work regulations or collective agreements. These instruments must ensure at least the minimum standards prescribed by the FD, while allowing the employer the discretion to provide a higher level of protection, thereby enhancing workers' safety and health beyond the statutory minimum.

Among the other *sui generis* obligations of the employer, several aspects are of particular significance. The employer bears primary responsibility for assessing risks to the safety and health of workers, including those risks to which groups of workers exposed to specific hazards may be subject. This responsibility further encompasses determining the appropriate protective measures to be implemented, including the careful selection and proper use of protective equipment. The employer is also required to maintain comprehensive records of occupational accidents that result in an employee being unable to perform their work for more than three consecutive working days. Such information is submitted to the competent national authorities, which subsequently compile detailed reports on occupational accidents. The ultimate recipient of these reports is the Statistical Office of the European Union, which systematically publishes annual data on the total number of occupational accidents throughout the EU, thereby enabling robust monitoring and evaluation of workplace safety trends.

Article 7 of the FD provides a detailed framework for protection and prevention services, including the minimum competency criteria required for appointed workers and external experts. The FD grants MS discretionary authority to determine the number of these experts, provided that their number is sufficient to effectively organize protection and prevention measures. This assessment must take into account the size and nature of the undertaking, the types of occupational risks involved, and the distribution of the workforce. This provision has led to notable variations in national regulations and practices concerning the fulfillment of these obligations, reflecting the diverse approaches and legal traditions of MS in implementing the FD. The institutionalization of a prevention culture in an organizational and legal context is reflected in the employer's duty to appoint one or more workers responsible for occupational risk protection and prevention within the undertaking or establishment. The employer must allocate sufficient time for them to fulfill these duties, and workers must not be placed at a disadvantage due to their activities. If internal experts are unavailable, the employer engages external specialists. MS autonomously determine the criteria for selecting worker representatives and external service providers, a practice that has resulted in a non-uniform approach across MS, reflecting the diversity of national legal frameworks. In addition, the employer's role extends beyond the organizational level to encompass responsibilities from the EU level, as well as obligations arising from normative frameworks established within national legislation. Most MS clearly define the employer's responsibilities for safeguarding all employees, including those belonging to special categories of workers, thereby affirming that the implementation of preventive measures remains fundamentally the employer's duty. These legal provisions not only ensure compliance with the minimum standards set forth by the FD but also actively promote the cultivation of a culture of safety and prevention within the workplace, reinforcing both legal accountability and organizational best practices [2].

4. SUPERVISION OF IMPLEMENTATION

The practical enforcement of EU legislation in the field of occupational safety and health, including the FD, is carried out by labor inspectors in close coordination with specialized agencies responsible for specific sectors, thereby ensuring the effective implementation of the regulations [5]. At the EU level, these responsibilities are performed by the Committee of Senior Labour Inspectors. The Committee began its activities informally in 1982 with the objective of assisting the European Commission in monitoring the transposition and application of European legislation within national legal systems. By Commission Decision (95/319/EC), the Committee was granted formal status and a mandate to provide opinions, either on its own initiative or at the request of the Commission [6].

This system has proven to be effective, as the Commission generally considers the Committee's opinions, thereby indirectly influencing and shaping further initiatives aimed at improving occupational safety and health across MS.

According to Article 18, MS were required to adopt the necessary laws and regulations to ensure compliance with the FD by 31 December 1992 and to notify the European Commission accordingly. Oversight of the FD's implementation involves five-yearly reporting by MS on its practical application, reflecting the perspectives of employers and workers. The Commission subsequently informs the European Parliament, the Council, the Economic and Social Committee, and the Advisory Committee on Safety and Health at Work, submitting periodic reports to these institutions. In addition, MS provide the Statistical Office of the European Union with annual data on occupational injuries, which the Office aggregates and publishes. Through these different mechanisms, the provisions of the FD are effectively complemented by a robust supervisory framework.

5. CONCLUSION

The Framework Directive represents the most significant legal instrument at the EU level in the field of occupational safety and health, given its foundational role in establishing overarching standards and principles. It has effectively institutionalized a culture of prevention, both within the organizational management of work processes and in the corresponding legal governance structures, thereby shaping the way workplace safety and health are approached across all member states. Its significance is particularly evident in the fact that the Framework Directive remains fully valid in its original form even today, serving as the enduring foundation of EU occupational safety and health law. A normative-legal and doctrinal analysis has unequivocally demonstrated the quality of the Framework Directive's text, accompanied by its conciseness and clarity. Meanwhile, numerous subsequent directives have been adopted to regulate in greater detail specific aspects of workplace safety and health, building upon the core principles and preventive framework established by the Framework Directive. Through the application of the principle of minimum harmonization, these directives have been integrated into the national labor law systems of the Member States, an outcome that would not have been possible had the Framework Directive, in its relatively concise provisions, not encompassed the essential elements of occupational safety and health. Substantively, the principle of prevention has emerged as the foundational basis for all further activities in this field, and the institutionalization of a prevention culture can be regarded as one of the most significant innovations in European labor law, representing a key consequence of the Framework Directive. Furthermore, both by its nature and its title, the Framework Directive continues to serve as the primary foundation for the regulatory framework governing occupational safety and health within national legislation, whose implementation is assessed and applied *in concreto*. In conclusion, its enduring relevance highlights the Framework Directive's role as a cornerstone of EU occupational safety and health policy.

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Original scientific paper

RESTAURANTS GASTRONOMIC OFFER SATISFACTION IN CROATIA

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Abstract : *The purpose of this paper is to research guest satisfaction with Croatia's restaurant gastronomic offer. It analyzes visiting habits, motives for restaurant visits, types of gastronomic offers, and overall satisfaction. An online survey using Google Forms included domestic (N=148) and foreign (N=37) guests to Croatian restaurants. Data were analyzed with IBM SPSS Statistics Version 31. Results show the guests are very satisfied with the gastronomic offers.*

Keywords: *visiting habits, motives, gastronomic offer, satisfaction, restaurants, Croatia*

1. INTRODUCTION

The purpose of the research was to analyze satisfaction with the gastronomic offer in restaurants in Croatia. This research aimed to analyze restaurant visiting habits, motives for going to restaurants, and the level of satisfaction with the gastronomic offer of restaurants in the Republic of Croatia. The research was conducted from March to April 2026 via online questionnaire with 31 questions on a sample of 185 respondents. Visitor motivation was measured using a Likert scale created by Uysal et al. (1993) with 9 variables [1]. The satisfaction of the visitors and sharing experiences through social networks was measured using a Likert scale created by Bounincontry et al. (2017) with 5 variables [2] and loyalty was measured using a scale by Kim et al. 2010 [3] with 3 variables regarding satisfaction, future visit and recommendations. Other variables were adopted according to research in restaurants.

The structure of the respondents shows there were 79.5% domestic and 20.5% foreign visitors. Research focused on guests' satisfaction with the gastronomic offer of restaurants in the Republic of Croatia and aimed to examine restaurant-visiting habits, motives for visiting restaurants in

Croatia, and satisfaction with the quality of food, service, atmosphere, and overall experience. The survey used a structured questionnaire and a five-point Likert scale, where 1 indicated complete disagreement and 5 indicated complete agreement with the stated statements.

The following research questions were formed:

1. What are the most common guests' habits in Croatian restaurants?
2. What are the most common motives for going to restaurants?
3. Are the guests overall satisfied with the quality of food in Croatian restaurants?
4. What are the respondents most satisfied with?

The paper consists of four chapters. The introductory part, explaining the purpose, the goals and of the research questions, is followed by a description of the basic concepts in the theoretical framework, a description of the methodology and the results of the empirical research. The paper ends with the discussion part and the conclusion.

The research results can be useful to restaurant owners, tourist boards, and other stakeholders in the tourism and hospitality sector when planning the development of the gastronomic offer. The gastronomy is an important element of the tourist offer and can significantly contribute to the competitiveness of a destination.

2. LITERATURE REVIEW

Motivation is a crucial driver of customer behaviour [4]. Understanding the guests' motives for attending an event is essential and a key concept in creating an offer for visiting or personalizing that offer to suit their needs as well as in building satisfied guests willing to come back and in building their loyalty [5]. Many others have researched the relationship between motivations, satisfaction and loyalty [1], [4], [5], [6], [7], [8]. McIntosh et al. (1995) defined four categories of motivations: physical, cultural, interpersonal and status and prestige [9].

Satisfaction is the outcome of a subjective evaluation of whether the selected alternative meets or exceeds expectations [3]. It is consumer judgment about goods and services, the outcome of a subjective evaluation of whether the selected alternative meets or exceeds expectations [3]. Satisfaction has a positive influence on the visitors' post purchase behaviour such as recommendations and intention to revisit [8]. Loyalty is defined as repeat purchase behaviour and it is characterised in terms of repurchase intentions, WOM communications, and recommendations [11]. Satisfied visitors may revisit a place and recommend it to others [11]. There is a correlation between customer satisfaction and their future intention [3]. Satisfaction affects loyalty and post-purchase behaviours [12].

3. FINDINGS

The analysis of sociodemographic characteristics of the respondents revealed a diverse sample structure. A larger number of female respondents (66.8%) participated in the study, while men made up a smaller part of the total sample (33.2%). The most represented age group was the group of

respondents between 18 and 25 years of age (65.8%), while 26 and 35 years (15.2%) and more than 36 years old (19.3%) also participated in the study. According to the level of education, the largest number of respondents had completed secondary school (46.7%) and university education (39.1%). In terms of employment status, employed and self-employed respondents dominated, while a smaller part of the sample was made up of students. The analysis of monthly income showed that the largest number of respondents had a monthly income up to 700 EUR (30.4%), from 1.001 to 1.500 EUR (25.5%) and from 1.501 to 2.000 EUR (20.7%). There were 20.5% foreign visitors surveyed, of which 26.3% came from France, 23.7% from Bosnia and Herzegovina, 13.2% from Slovenia and 13.2% from Austria, 5.3% came from Germany, Australia, the Netherlands and Ireland, 2.6% of the respondents were from Canada.

The majority of the respondents stated they visit restaurants in Croatia several times a year (41.6%), while foreign guests visit restaurants in Croatia mostly 6-10 times a year (42.11%). Such results indicate a relatively high level of involvement of respondents in gastronomic experiences and their familiarity with the restaurant offer in the Republic of Croatia. When it comes to the geographical area of visiting restaurants, the largest number of the respondents visit restaurants in the continental part of Croatia (48.1%), and foreign guest visit the Adriatic (47.37%), while a proportion of the respondents (30.8%) visit restaurants in both continental and coastal parts of the country. An analysis of the types of restaurants respondents visits most frequently revealed that the most common choices are family restaurants (49.7%), fast-food restaurants (49.7%), restaurants serving traditional Croatian cuisine (48.1%), taverns and pizzerias (47.6%). Foreign guests mostly visit international restaurants (39.47%) and traditional restaurants (34.21%). These results highlight the importance of traditional culinary offerings, as well as the significance of accessible, everyday dining options.

One of the goals of the research was to determine the main motives for respondents to visit restaurants in the Republic of Croatia. The results of the research showed that respondents expressed the highest level of agreement with the statements that they visit restaurants to socialize with friends and family (85.9%), to enjoy the atmosphere in Croatian restaurants (85.8%), and to enjoy the gastronomic offer (81.5%). A large number of respondents also stated that they visit restaurants because they want to try new dishes and gastronomic experiences (71.2%), and to relax and escape from everyday obligations (55.1%). A lower level of agreement was recorded with the statement that the attractive location of a restaurant is the key motive for visiting a restaurant (69%). Foreign guests preferred good entertainment while in Croatian restaurants (84.21%), gastronomic offerings (81.57%) and atmosphere in restaurants (81.57%). These results confirm that restaurants today are not only a place for consuming food, but also an important form of social and experiential leisure time. A pleasant atmosphere, interior design, ambiance, and a sense of relaxation are important elements of the overall gastronomic experience.

An analysis of the attitudes of guests about the gastronomic offer of restaurants in the Republic of Croatia revealed a predominantly positive opinion about the quality of food and service. The majority of the respondents agreed with the statement that the food in restaurants is of high quality (79.9%) and that the restaurants offer a diverse gastronomic offer. The respondents expressed particularly high levels of agreement with statements related to the hospitality of the staff (86.84%), the professionalism of the service (72.8%), and the cleanliness and tidiness of the restaurant premises (89,47%), foreign guests are also satisfied with the hospitality of the staff (82.8%), the professionalism of the service (86.84%) and the cleanliness and tidiness of the restaurant premises (89.47%). Such results show that the quality of service and the attitude of the staff towards guests play a significant role in shaping overall consumer satisfaction. The respondents also mostly positively assessed

the restaurant's atmosphere, believing that it is the atmosphere that significantly contributes to the gastronomic experience and overall satisfaction with visiting a restaurant. When it comes to the diversity of the offer, the respondents positively assessed the offer of traditional Croatian dishes, which confirms the importance of authentic gastronomy in shaping the tourist and hospitality offer of the Republic of Croatia. On the other hand, slightly lower scores were recorded for the statement relating to the diversity of vegan and vegetarian offerings. Such results indicate the possibility of further development and adaptation of the gastronomic offer to contemporary food trends and the needs of different groups of guests. Also, some respondents expressed some dissatisfaction with the price-quality ratio, which suggests that consumers are becoming increasingly sensitive to the value they get for the price paid.

The survey results showed that the majority of respondents were satisfied with their overall experience in restaurants in the Republic of Croatia (91.3%) and foreign guests were also satisfied (81.31%). A large number of the respondents stated that they would gladly return to the same restaurants (91.3%) and foreign guests (81.53%), indicating a certain level of loyalty towards catering establishments with which they have had positive previous experiences. In addition, a large number of the respondents said they would recommend restaurants in Croatia to others (91.9%), and foreign guests (97.36%). Willingness to recommend is an important indicator of guests' satisfaction and indicates a positive image of the restaurant offering among guests.

The positive results of the survey confirm that the quality of food (79.9%), the professionalism of the staff (41.3%), the pleasant atmosphere (51.1%), and the authenticity of the gastronomic offer play a key role in creating guest satisfaction and their future intention to visit the restaurant again. Based on the conducted data analysis, conclusions were drawn about consumer satisfaction with the gastronomic offer of restaurants in the Republic of Croatia. The obtained survey results enabled a more detailed understanding of consumers' habits, motives, and perceptions regarding the restaurant offer. The survey results showed that respondents generally have a positive opinion about the gastronomic offer of restaurants in the Republic of Croatia. In particular, the quality of food (44.6%), the hospitality of the staff (42.4%), the pleasant atmosphere (51.1%), and the variety of traditional Croatian dishes (38.6%) stand out as key elements of guest satisfaction. The restaurants represent an important part of social life and leisure time. Respondents do not visit restaurants solely for the purpose of consuming food, but also for socializing (60.9%), relaxing (38.6%), and gaining new gastronomic experiences.

Despite the predominantly positive results, the research also pointed to certain shortcomings in the gastronomic offer. The most pronounced shortcomings relate to the limited offer of vegan and vegetarian dishes (47.3%) and the perception of some respondents that the price of food does not always correspond to the quality of the offer.

The results obtained can serve as guidelines for catering establishments to improve their business and adapt to the needs of modern consumers. Special attention should be paid to the development of a more diverse gastronomic offer, adaptation to different eating habits, and maintaining high-quality service and professional relations with guests.

3.1. Research limitations

The research was conducted on a limited sample of respondents, only online respondents, so the results may not fully represent the views of the entire population. There were only 20.5% foreign guests, the research must be expanded to foreign tourists in Croatia and analyze their attitudes. Although a satisfactory number of the respondents participated in the survey, not all

age groups, income levels, and lifestyles of consumers were equally represented, which can limit the generalizability of the results, primarily to the territory of Croatia, where the largest number of respondents came from. The future research, must be on a larger and more representative sample of respondents and include additional variables such as the frequency of tourist trips, preferences of foreign guests, or comparisons of different regions of the Republic of Croatia. It is also recommended to conduct a more detailed statistical analyses, such as correlation and factor analysis, in order to more precisely determine the relationships between guest satisfaction, service quality, gastronomic offer, and guest loyalty.

4. DISCUSSION AND CONCLUSION

In conclusion, it can be emphasized that the gastronomic offer of restaurants in the Republic of Croatia has significant potential for further development. Maintaining the quality of food and service, developing an authentic gastronomic offer, and adapting to modern trends and guest expectations are key factors in successful restaurant operations and developing the competitiveness of the Croatian hospitality and tourism industry. This research contributed to guest satisfaction with the gastronomic offer of restaurants in the Republic of Croatia, motives for visiting, perceptions of service quality, and intention to return and recommend to others.

Based on the conducted research, it can be concluded that the respondents are mostly satisfied with the gastronomic offer of restaurants in the Republic of Croatia. The quality of the food, the professionalism and hospitality of the staff, the pleasant atmosphere of the restaurant, and the variety of traditional Croatian dishes were particularly positively rated. The results show that restaurants today are not only a place for food consumption, but also an important space for socializing, relaxing, and creating gastronomic experiences, which is in line with previous research [3], [12].

The research also confirmed that the most important motives for visiting restaurants are enjoying the gastronomic offer, spending time with family and friends, and escaping from everyday obligations. The majority of the respondents expressed their willingness to visit restaurants again and recommend them to others, which indicates a high level of overall satisfaction and guest loyalty. Previous research also proved a high relationship between satisfaction and loyalty [5],[10],[11], [12].

Regarding foreign guests, the results show that foreign guests most often visit restaurants in Adriatic Croatia (47.37%) and prefer international cuisine (39.47%), although traditional Croatian dishes are also highly rated (34.21%). Their main motive for coming is good entertainment while in Croatian restaurants (84.21%), gastronomic offerings (81.57%) and atmosphere in restaurants (81.57%). The respondents are very satisfied with the food quality (78.95%), staff professionalism (81.58%), atmosphere (73.69%), and cleanliness (89.47%). The guests who visited Croatian restaurants are fully satisfied with them (81.31%), they plan to come back (81.53%). Most believe the restaurants offer a diverse range and are worth recommending to others (97.36%), while vegan and vegetarian options are neutral answers (47.37%). In conclusion, restaurants in Croatia have a very positive image among foreign guests, who report high satisfaction and a strong willingness to return and recommend, but the price-quality ratio and the variety of special food options still need improvement.

Despite the positive results, certain shortcomings in the gastronomic offer were also noted. The most room for improvement exists in expanding the vegan and vegetarian offer and improving the price-quality ratio of the service, since some respondents believe that prices are not always in line

with the quality of the experience offered. The results obtained can be useful for restaurant owners, hospitality workers, and tourist boards as guidelines for further improving the quality of service and adapting to modern guest needs. Maintaining high-quality food and service, developing an authentic gastronomic offer, and adapting to new food trends represent key factors in the development of the competitiveness of the Croatian hospitality industry and gastronomic tourism. Based on the research results, all research questions have been answered. The results indicate a high level of satisfaction with the gastronomic offer of restaurants in the Republic of Croatia, while simultaneously recognizing the need to improve vegan and vegetarian offerings and better align price and service quality.

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Original scientific paper

EXPERIENCES OF GENDER DISCRIMINATION AMONG OCCUPATIONAL SAFETY AND HEALTH PROFESSIONALS IN THE WORKPLACE IN THE REPUBLIC OF CROATIA

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Abstract: *The field of occupational safety and health is traditionally perceived as a technical and predominantly "male" profession, although in recent years the number of women entering education and employment in this field has been increasing. The aim of this paper is to examine the experiences of occupational safety and health professionals related to gender discrimination in the workplace. The empirical part of the study is based on a combination of qualitative and quantitative approaches. Two semi-structured interviews were conducted with occupational safety and health professionals, along with an anonymous survey among professionals from various organisations in the Republic of Croatia (N = 37). The results indicate that more than half of the respondents have experienced some form of unfavourable treatment related to their gender during their professional careers. The most common forms include undermining professional competence, stereotypes about the profession being a "male occupation", and inappropriate comments in the work environment. The findings highlight the need for further strengthening of professional standards and the promotion of gender equality in the field of occupational safety and health.*

Keywords: *occupational safety and health, gender discrimination, women occupational safety and health professionals, gender equality, workplace.*

1. INTRODUCTION

Although social norms are changing, certain occupations are still perceived as "male-dominated", based on the assumption that women cannot perform the same jobs as successfully as men in equivalent positions. This perception is particularly evident in the field of occupational safety, where

the traditional focus of the profession and related research has been on preventing risks in visibly hazardous occupations predominantly performed by men, such as those in the construction and mining sectors. [1] The consequences of this legacy remain evident today. According to a study conducted by L'Oréal and ERM in the United States, women account for only 19% of the occupational safety workforce, compared with nearly 50% of the overall workforce, while respondents identified the so-called "credibility gap" as one of the main barriers to career advancement. [2]

Within the field of occupational safety, the role of occupational safety professionals is of particular importance. Their responsibilities include providing professional assistance to employers, participating in the preparation of risk assessments, monitoring the implementation of occupational safety measures, and training workers to perform their work safely (Article 21 of the Occupational Safety Act, Official Gazette 71/14, 118/14, 154/14, 94/18, and 96/18). [3][4] The Ordinance on the Performance of Occupational Safety Activities (Official Gazette 126/19 and 154/22) further prescribes the requirements that Level I and Level II occupational safety professionals must meet in order to perform occupational safety duties either for an employer or within an authorised legal entity. [5]

Occupational safety is essential for the proper functioning of every working environment. Gender discrimination experienced by women working as occupational safety professionals is not always direct; it often takes the form of indirect prejudice and the underestimation of their abilities, which can have long-term effects on their professional development, motivation, and psychosocial well-being.

Discrimination is defined as treatment that places a person at a disadvantage, without objective justification, on the basis of personal characteristics such as sex, race, age, or other status, whereby the individual's abilities are not assessed on their own merits but rather on the basis of stereotypical assumptions. [6] In the field of employment and working conditions, discrimination manifests itself through inequalities in recruitment, career advancement, vocational guidance, vocational education and training, and retraining (Article 7(4) of the Labour Act, Official Gazette 93/14, 127/17, 98/19, 151/22, 46/23, and 64/23). [7]

Sex-based discrimination means any distinction, exclusion, or restriction made on the grounds of sex that has the effect or purpose of impairing or nullifying the recognition, enjoyment, or exercise of human rights and fundamental freedoms in the political, economic, social, educational, cultural, civil, or any other sphere, on the basis of equality between women and men (Article 6(1) of the Gender Equality Act, Official Gazette 82/08, 125/11, 20/12, 138/12, and 69/17). [8]

Protection against discrimination in employment in the Republic of Croatia is regulated by several legislative acts. The Anti-Discrimination Act (Official Gazette 85/08 and 112/12), [9] as well as the previously mentioned Gender Equality Act, distinguishes direct discrimination, indirect discrimination, harassment, and sexual harassment as specific forms of discriminatory treatment (Articles 2–3 of the Anti-Discrimination Act and Articles 7–8 of the Gender Equality Act), [9][8] while the Labour Act refers to these special acts in its provisions (for example, Article 6(4)). [7] At the international level, protection against discrimination has been provided since 1958 through the International Labour Organization's Discrimination (Employment and Occupation) Convention (Convention No. 111, Official Gazette – International Treaties 5/2000), which requires each Member State for which the Convention is in force to declare and pursue a national policy designed to promote equality of opportunity and treatment in respect of employment and occupation, with a view to eliminating all forms of discrimination in this area (Article 2 of the Discrimination (Employment and Occupation) Convention). [10] The Convention has been ratified by 175 countries, including the Republic of Croatia. [11] At the European Union level, Directive 2006/54/EC (Directive 2006/54/EC of the European Parliament and of the Council of 5 July 2006 on the implementation of the principle

of equal opportunities and equal treatment of men and women in matters of employment and occupation, OJ L 204, 26 July 2006) [12] prohibits discrimination on the grounds of sex in relation to access to employment, promotion, vocational training, and working conditions, including pay and dismissal, [13] while Directive 2010/41/EU (Directive 2010/41/EU of the European Parliament and of the Council of 7 July 2010 on the application of the principle of equal treatment between men and women engaged in an activity in a self-employed capacity and repealing Council Directive 86/613/EEC, OJ L 180, 15 July 2010) [14] protects self-employed persons against discrimination. [15] Directive (EU) 2024/1500 (Directive (EU) 2024/1500 of the European Parliament and of the Council of 14 May 2024 on standards for equality bodies in the field of equal treatment between women and men and equal opportunities in matters of employment and occupation, and amending Directives 2006/54/EC and 2010/41/EU, OJ L, 2024/1500, 29 May 2024) [16] further establishes common standards for equality bodies in the Member States of the European Union by laying down rules on their mandate, resources, independence, and powers, with the aim of ensuring more effective protection against sex-based discrimination in employment and occupation. For this purpose, it also amends Directives 2006/54/EC and 2010/41/EU. [17]

Despite this legislative framework, the discrimination experienced by women occupational safety professionals does not arise solely from the workplace itself, but also from a system that has too often been designed around a "male" norm. Occupational safety policies and practices continue to rely predominantly on gender-neutral models that implicitly treat men as the default standard, with the result that the risks faced by women workers in different occupations are less likely to be recognised or reflected in official statistics. [18][19] Many occupational safety standards are still based on research conducted on male populations and in sectors with predominantly male workforces, reflecting a culture in which masculinity is regarded as the neutral norm. [20] For this reason, the International Labour Organization (ILO) emphasises that prevention policies and strategies must take gender differences into account in order to be equally effective for both women and men. [21]

This systematic invisibility of the risks faced by women workers is also reflected in the everyday position of women occupational safety professionals, who, as noted above, frequently encounter indirect forms of prejudice and the underestimation of their abilities. Prolonged exposure to such discrimination may lead to feelings of diminished self-worth, loss of motivation, and burnout, while psychological consequences such as stress and anxiety may also impair the overall performance of the organisation. [22]

In light of the above, the aim of this paper is to examine the experiences of women occupational safety professionals regarding sex-based discrimination in the workplace in the Republic of Croatia by combining qualitative and quantitative research approaches.

2. RESEARCH METHODOLOGY

The study was conducted during 2025 using a combination of qualitative and quantitative research approaches in order to examine the personal experiences of women occupational safety professionals within a broader context supported by numerical data on the prevalence and forms of sex-based discrimination in the profession.

The qualitative component consisted of two semi-structured interviews with women occupational safety professionals. Both interviews were conducted using the same set of questions to collect participants' personal experiences of sex-based discrimination in the workplace and the challenges they encounter in their profession.

The quantitative component was conducted through an anonymous online questionnaire created using Google Forms and distributed to women occupational safety professionals via WhatsApp, Instagram, Viber, Messenger, and e-mail. Data were collected over a period of 30 days, and a total of N = 37 women occupational safety professionals participated in the study. The questionnaire consisted of 14 questions divided into two sections. The first section collected basic demographic and professional information about the participants (age, years of work experience, employment sector, and current position), while the second section comprised statements and questions designed to assess the prevalence and impact of sex-based discrimination, the availability of reporting mechanisms, and participants' awareness of their rights, concluding with an open-ended question inviting additional comments.

The sample consisted of women employed as occupational safety professionals in different organisations and sectors (both public and private), regardless of their length of professional experience. Although the sample is not representative of the entire population of women occupational safety professionals in Croatia, it provides valuable insight into the participants' subjective experiences. The data were analysed using descriptive statistical methods and are presented as percentages of responses.

Participation in the study was voluntary and anonymous, ensuring the protection of the participants' privacy.

3. RESULTS AND DISCUSSION

The interviews were primarily used to gain a deeper understanding of the participants' experiences rather than to generalise the findings. The two interviews conducted with women occupational safety professionals (with professional experience since 2018 and seven years, respectively) revealed several common patterns. Both participants reported experiencing the devaluation of their professional competence at the very beginning of their careers. When enquiring about an internship, the first participant was met with the employer's remark, "What would I do with women on a construction site?!", while the second participant, despite having qualifications equal to those of other candidates, was passed over in favour of a less experienced male candidate "because he was a man." The first participant further described an incident in which, following a mistake made by her male colleague, she was the one called in for a meeting and subjected to a verbal attack, whereas her colleague faced no consequences. The second participant identified the repeated use of gendered forms of address instead of professional communication (e.g. "sweetheart" and "doll") as a recurring pattern, perceiving such behaviour as a sign of disrespect towards her professional role.

Both participants reported a lack of support when confronted with discriminatory treatment. In the first case, discriminatory behaviour most often originated from supervisors, while in the second, colleagues responded passively, as though such behaviour were normal and acceptable. The first participant identified the greatest obstacles as the persistent underestimation of women's professional competence and the lack of solidarity even among women themselves. By contrast, the

second participant perceived the main obstacles as stemming from management's attitude towards the occupational safety profession itself, which was marginalised and regarded as "a cost rather than an investment."

The participants adopted different coping strategies. The first responded by suppressing her emotions and confiding in a colleague, noting that she associated some of her health problems with work-related stress. The second chose to respond directly and assertively in order to establish clear standards of respectful behaviour. As possible solutions, both participants emphasised the responsibility of those in leadership positions. The first advocated more frequent labour inspections, while the second stressed the importance of managers setting an example through respectful conduct that employees are likely to follow. Both encouraged young women to persevere in the profession and to build self-confidence.

A total of 37 women occupational safety professionals participated in the anonymous online survey. In terms of age, the largest proportion of respondents (54.1%; n = 20) were up to 30 years old, 37.8% (n = 14) were between 32 and 45 years old, while respondents over the age of 46 accounted for only 8.1% (n = 3) of the sample. The sample therefore consisted predominantly of younger women occupational safety professionals. Regarding work experience, 57% (n = 21) of respondents had between one and five years of experience, while 27% (n = 10) had between six and ten years of experience. A further 8% (n = 3) had less than one year of experience, and 8% (n = 3) had more than ten years of experience. The majority worked in the private sector (68%; n = 25), while 32% (n = 12) worked in the public sector. According to their position, 78% (n = 29) worked as occupational safety professionals, 11% (n = 4) as team leaders, while the remaining 11% (n = 4) performed other roles (workers' occupational safety representatives, preparation of risk assessments in authorised companies, fire safety activities, and teaching activities).

Of the 37 respondents, 62% (n = 23) stated that they had experienced less favourable treatment because of their sex at least once. When asked about the areas in which they did not have the same opportunities as their male colleagues (multiple answers were possible), the most frequently reported were comments or behaviour undermining their professional competence because of their sex (n = 18) and a lack of respect and cooperation from colleagues (n = 16), followed by the feeling that their professional opinions were not taken seriously (n = 15), unequal access to employment and the suggestion that men have better knowledge of the field (n = 12 each), lower pay (n = 11), more limited access to important tasks (n = 8), and a lack of career advancement despite meeting the required conditions (n = 6). Ten respondents had not experienced unequal treatment or were unsure of their answer. These findings directly correspond to the concept of the "credibility gap", which the ASSP identifies as a key barrier to the career advancement of women in the occupational safety profession.

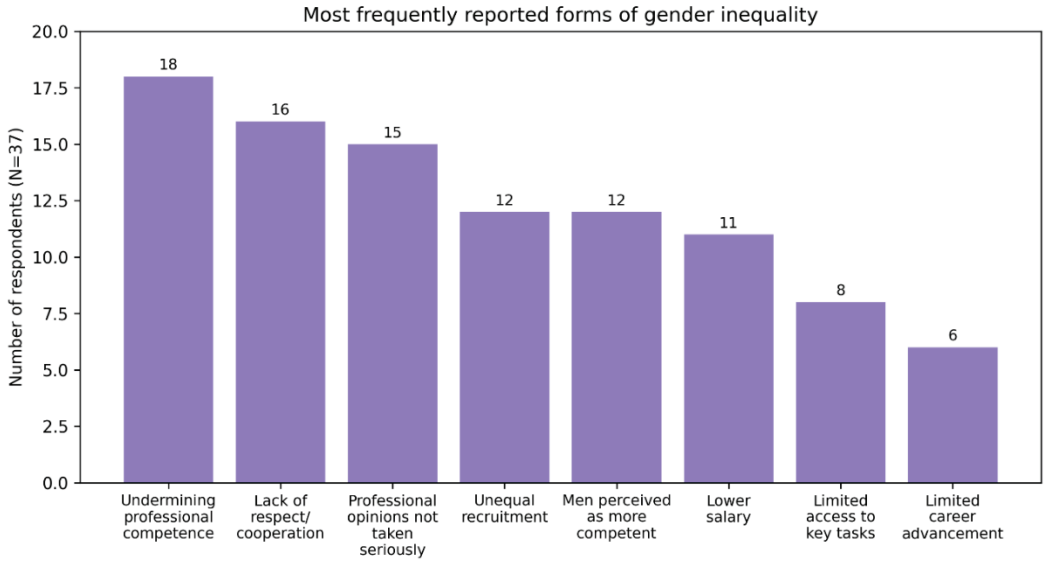


Figure 1. Reported forms of gender inequality in the workplace (N = 37)

Employers and supervisors were most frequently identified as the source of discrimination (n = 16), followed by colleagues working in the field (n = 13). A smaller number of respondents identified clients/service users (n = 8), external associates or contractors (n = 2), and state inspectors or institutions (n = 1) as the source, while twelve respondents had not experienced discrimination and two were unsure. The predominance of supervisors as the source of discrimination corresponds to the experiences of both interviewed occupational safety professionals, who reported that support in such situations was lacking precisely from those in higher hierarchical positions. However, the finding that discrimination also occurs outside the immediate work team - from clients and external associates -indicates that the problem extends beyond the boundaries of the employing organisation. Regarding frequency, 35% (n = 13) had never experienced discrimination, 27% (n = 10) had experienced it once or twice, and a further 27% (n = 10) had experienced it occasionally (several times a year). Eight percent (n = 3) had experienced discrimination frequently (at least once a month), while one respondent experienced it almost every day.

When asked about the level of gender equality in the working environment, 54% (n = 20) considered that gender equality generally exists despite occasional challenges, while 22% (n = 8) believed that it is fully respected. In contrast, 16% (n = 6) frequently observed gender inequality, and 8% (n = 3) considered women to be significantly undervalued, indicating that even among respondents who formally perceive gender equality to exist, experiences are not uniform. Although 38% (n = 14) considered that the discrimination they had experienced had not affected their career, 24% reported a negative impact (8% significant and 16% moderate), while 8% (n = 3) were unable to assess its extent. The remaining 30% (n = 11) had not experienced discrimination at all. This suggests that the consequences of discrimination are not always immediately recognised or articulated but, as also shown by the interviews, may be reflected in health problems associated with stress.

With regard to institutional mechanisms, 70% knew whom they would contact in the event of discrimination, 19% did not know, and 11% were unsure. However, only 35% stated that clearly defined and publicly available reporting mechanisms existed in their workplace, 19% stated that such mechanisms existed but were not sufficiently clear, 32% stated that no such mechanisms existed, and 14% were unsure. This discrepancy between knowing whom to contact and the actual

existence of formal reporting mechanisms suggests that protection in practice often relies on informal rather than institutionalised channels, which partly explains why as many as 84% of respondents considered the introduction of additional measures to promote gender equality within the profession to be beneficial.

The respondents' open comments further illustrate the range of experiences. Some respondents who had not experienced discrimination had no particular comments for that very reason, while several emphasised that support and respect came precisely from employers and supervisors, whose example was then followed by other employees. In contrast, one respondent described a series of patterns of workplace bullying experienced by women who enter the profession without "connections or assistance", including belittlement, intimidation, the spreading of false information, the deliberate assignment of other employees' work to make them appear incompetent, denial of a salary increase despite meeting expectations, and harassment through messages and inappropriate physical contact. She noted that whether a woman succumbs to or resists such pressure largely depends on her own perseverance. Interestingly, some respondents also associated discriminatory behaviour with the perpetrators' lower level of education. Another respondent linked discrimination in recruitment to the physical appearance of female candidates, while a third emphasised the importance of educating children about recognising sex-based discrimination from an early, pre-school age. Positive comments also emerged, with some respondents attributing greater meticulousness and higher-quality work to women than to their male colleagues, indicating that gender stereotypes within the profession may operate in both directions.

Table 1. Summary of the Key Research Findings (N = 37)

Indicator	Number	Percentage
Respondents who had experienced less favourable treatment because of their sex at least once	23	62%
Most common forms of inequality – comments/behaviour undermining professional competence	18	48.6%
Lack of respect and cooperation from colleagues	16	43.2%
Professional opinions are not taken seriously	15	40.5%
Unequal access to employment	12	32.4%
Suggestion that men have better knowledge of the field	12	32.4%
Lower pay compared with male colleagues	11	29.7%
More limited access to important tasks	8	21.6%
Lack of career advancement despite meeting the required conditions	6	16.2%
Sources of discrimination – employers/supervisors	16	43.2%
Sources of discrimination – colleagues working in the field	13	35.1%
Sources of discrimination – clients/service users	8	21.6%
Frequency – never	13	35%
Frequency – once or twice, or occasionally (several times a year)	20	54%
Frequency – frequently (at least once a month)	3	8%
Frequency – almost every day	1	3%
Perception of gender equality – "generally exists (despite occasional challenges)"	20	54%
Perception of gender equality – "fully respected"	8	22%

Indicator	Number	Percentage
Perception of gender equality – "frequently observes gender inequality"	6	16%
Knows whom to contact in the event of discrimination (Yes)	26	70%
Clearly defined and publicly available reporting mechanisms exist (Yes)	13	35%
Considers the introduction of additional gender equality measures to be beneficial	31	84%

Source: authors' research

4. CONCLUSION

The conducted research shows that sex-based discrimination against women occupational safety professionals in the Republic of Croatia remains a present phenomenon. More than half of the respondents had experienced some form of less favourable treatment because of their sex, most commonly in the form of the underestimation of their professional competence, inappropriate comments, and unequal access to career advancement, while supervisors and employers were identified as the most common sources of discrimination. The interview findings further confirm that discrimination rarely manifests itself through direct exclusion, but rather through more subtle forms of belittlement that have a long-term impact on the professional self-confidence and psychosocial well-being of women occupational safety professionals. At the same time, the findings show that discrimination did not discourage the respondents from continuing their professional careers; rather, for some of them, it encouraged greater perseverance and a stronger commitment to their professional competence.

The findings indicate the need for concrete changes in employers' policies and practices, including the introduction of regular training on recognising and preventing sex-based discrimination, the application of gender-balanced criteria in recruitment and appointments to managerial positions, the promotion of mentoring and networking among women occupational safety professionals, and the development of return-to-work programmes following maternity leave with the possibility of flexible working arrangements. Given that 84% of respondents consider additional measures to be beneficial, while formal reporting mechanisms are not always clear or accessible according to the respondents' experiences, strengthening institutional protection mechanisms appears to be as important as education.

The study has several limitations. The sample of 37 respondents was a convenience sample rather than a representative sample of the entire population of women occupational safety professionals in Croatia. Therefore, the findings cannot be generalised but instead provide insight into the subjective experiences of participants who were willing to share their experiences. The qualitative component of the study was based on only two interviews, which limits the depth of insight into the diversity of experiences within the profession. Future research should include a larger and more representative sample, compare experiences across different sectors and regions, and adopt a longitudinal approach that would enable the monitoring of the effects of the implemented measures on the level of gender equality within the profession.

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Professional paper

OPERATIONAL STAFF FOR SAFETY AND CIVIL PROTECTION IN PRIMARY AND SECONDARY SCHOOLS – ROLES AND CHALLENGES

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Abstract: *This paper examines the role, responsibilities, training requirements, and practical challenges faced by operational staff tasked with safety and civil protection in Croatian primary and secondary schools. The introduction of this position followed the adoption of new school safety measures—prompted by an attack at Prečko Primary School in Zagreb in December 2024—as well as a broader need to strengthen security within educational institutions. The paper analyzes the relevant legal and regulatory framework, including the Protocol on Entry and Exit Control in Educational Institutions, amendments to regulations governing the status of administrative and technical school staff, and the training program for acquiring the partial qualification of an operational staff member for safety and civil protection in schools. The analysis highlights the need for clearer regulation regarding the legal basis, conditions, procedures, and accountability mechanisms associated with the exercise of specific powers. The paper also addresses challenges related to professional status, the standardization of equipment and appearance, training, and the integration of operational staff into the school environment. It concludes that while the introduction of operational staff constitutes a vital component of the school safety system, further development and clarification of the regulatory framework are required to ensure the lawful, consistent, and effective performance of their duties.*

Keywords: *operational staff, school safety, civil protection, primary schools, secondary schools, school security, use of coercive measures*

1. INTRODUCTION

On December 20, 2024—the last day of the first school term, a 19-year-old former student of Prečko Elementary School in Zagreb, known to have mental health issues, entered the school armed with a knife. He killed a 7-year-old student in the attack, while a teacher and several students were seriously injured. The perpetrator was found at a nearby health center following a suicide attempt.

The entire public was shocked and in disbelief—especially because the victim was a first-grade primary school student and the crime took place during the pre-Christmas and New Year holiday season.

The public demanded answers and urgent action from the institutions.

During 2025, The Ministry of Science, Education and Youth adopted a series of regulations that included enhanced security measures in primary and secondary schools, as well as the introduction of a new position in those schools: Operational Officer for Security and Civil Protection.

2. LEGAL FRAMEWORK AND ROLE OF OPERATIONAL STAFF

2.1. History of incidents in schools in Croatia

Even before the incident at the elementary school in the Prečko neighborhood of Zagreb, Croatia had a history of violence and crime in its elementary and secondary schools.

The first such incident was recorded on October 9, 1972, when Milorad Vujinović—then a fourth-year student at the Vladimir Nazor Gymnasium in Zadar—used his father's pistol to shoot and kill 46-year-old teacher Vice Vlatković on the school staircase, and seriously wounded 34-year-old teacher Gojko Matulina, who later succumbed to his injuries.

In October 1999, at an elementary school in Sesvete, Ivan Krišto killed Ante Č., seriously wounded his wife Cvita, and caused minor injuries to their seven-year-old son. The incident was sparked by a dispute between children, for which the parents had been summoned to the school for a meeting; the grandfather, Ivan—who committed the crime—showed up at the school uninvited.

In March 2001, a fourteen-year-old student at a vocational school in Sisak used an M-48 rifle to seriously wound a 16-year-old student and cause minor injuries to a teacher, Snježana Matić. The incident was triggered by teasing among the students and a fight.

In June 2001, Josip Kostanjević (17), a student at the Mining and Chemical High School in Varaždin, killed teacher Josip Medvedović in the schoolyard and then took his own life. The motive was a failing grade in geography.

In June 2001, at the Maritime School in Split, a 17-year-old student fired shots in the classroom, but fortunately, no one was injured. The incident was triggered by a failing grade.

In December 2005, a third-year high school student from Makarska stabbed his teacher, Zdravko Pervan, with a knife during a Croatian language class while the teacher was reading excerpts from *Germinal*.

In 2006, on a school playground in Ploče, an 18-year-old student killed a 17-year-old classmate, inflicting eight stab wounds to his head and neck.[1]

None of the events described provoked a reaction from the public and institutions quite like the crime in Prečko.

2.2. Crime at the Prečko school and new security measures

The murder of a seven-year-old boy shocked all of Croatia and beyond. Regarding the legal framework for safety in primary and secondary schools, the Act on Education in Primary and Secondary Schools serves as the fundamental document. The section titled "Safety and Health Protection in School Institutions" stipulates that school institutions are required, among other things, to create conditions for the healthy mental and physical development and social well-being of students, to prevent unacceptable forms of behavior, **and to ensure student safety**. In the section concerning the protection of students' rights, the Act states: Teachers, expert associates, and other staff members in school institutions are required to take measures to protect students' rights and to immediately report any **violation of those rights—particularly instances of physical or mental violence, sexual abuse**, neglect or negligent treatment, abuse, or exploitation of students—to the school principal, who is then obliged to report the matter to the social welfare authority or another competent body.[2]

Student safety is also addressed by the Ordinance on the Procedures to be Followed by Educational Staff in Schools Regarding Measures to Protect Students' Rights and the Reporting of Any Violations of Those Rights to Competent Authorities.[3]

As can be seen, the section of the Act addressing safety makes no mention of security measures, operational personnel, their duties, powers, professional standards, or related matters.

As an urgent response to the crime, the Ministry of Science, Education and Youth issued the Protocol on Entry and Exit Control in School Institutions on January 2, 2025, [4] which stipulates, among other things, the following:

- the Protocol was developed with the aim of ensuring greater safety in school institutions, protecting students and all staff within school institutions, and preventing potential high-risk situations,
- the rules defined by the Protocol apply to all persons while present on school premises,
- all students, staff, parents, and other external visitors must be familiar with the Protocol and adhere to it,
- school institutions are required to align their internal documents (school rules of conduct, internal protocols for crisis situations, etc.) with the Protocol,
- if a school operates at multiple locations and/or shares premises with entities such as faculties or other institutions, managing entry and exit security requires additional coordination and adaptation to ensure the consistent and safe implementation of the Protocol across all locations and in specific situations.

As **urgent measures,** the Protocol requires school institutions to:

- urgently check and ensure the technical adaptation of all school entrance doors;
- keep school entrance doors, as well as all other entrances and exits, locked throughout working hours while ensuring that evacuation exits remain functional, except in special circumstances approved by the principal;
- unlock doors to allow students to enter before the school day begins and exit after it ends—generally 30 minutes prior to the start of classes and 15 minutes after they finish—in accordance with the specific school's operational organization;

- assign staff to monitor the school entrance during working hours.
- if unusual behavior by individuals is observed on school premises, or if unlawful behavior or conduct endangering the safety of persons within the school is detected, the principal and the police must be notified immediately.
- students are not permitted to leave the school premises during short breaks.
- during the long break, primary school students are not permitted to leave the school's outdoor grounds.
- the school is required to establish rules and procedures for announcing visits and entering the school premises.
- if the school has multiple entrances, it must designate a single, unified entrance for all parents and visitors.
- parents may enter the school premises only at an agreed-upon time with prior notice or upon the school's invitation.
- a school staff member is required to meet the visitor at the entrance and escort them out of the school premises after the meeting,
- **a staff member responsible for monitoring entry to the school premises is required to verify the identity of any person entering the school by checking their identity card** or another appropriate document bearing the person's photograph.

Entry to the school will be denied to any person who refuses this check.

- all visitors who are not school staff or students must be logged in, escorted by a staff member to the designated location, and escorted out of the school premises.
- for safety and security reasons, **the staff member responsible for monitoring entry to the school premises may conduct security checks** of:
    - **students** and their belongings (clothing, bags, etc.)
    - **other persons entering the school** and their belongings (bags, etc.).

Security checks of students and their belongings may also be conducted by educational staff during

classes. Items capable of causing injury or other illicit items will be temporarily confiscated; the principal, professional support staff, parents, and the police (where conditions for police intervention are met) will be notified of their discovery.

Entry to the school will be denied to persons who do not consent to such checks.[4]

It can be seen that the Protocol mentions the employee of the school institution in charge of monitoring entrances to the premises of the school as the person who will operationally implement the above measures, and his powers include checking the identity of persons and security checks of persons. Some schools have even hired private security personnel as a safety measure.

2.3. Introduction of the new position of Operational Officer for Security and Civil Protection

In April 2025, the Ministry of Science, Education and Youth is introducing amendments to two ordinances: the Ordinance on the Scope of Work of Secretaries and Administrative-Technical and Auxiliary Tasks Performed in Primary Schools, and the Ordinance on the Scope of Work of Secretaries and Administrative-Technical and Auxiliary Tasks Performed in Secondary Schools. Both ordinances are being amended to include articles regarding the employment of an Operational Staff Member for Safety and Civil Protection—based on the prepared Assessment of the Current Situation and Risk Analysis and the School Institution's Safety Plan—whose duties include:

- supervising access control to the school institution, and monitoring and securing school property and premises,
- participating in the organization and implementation of basic civil protection measures and performing maintenance tasks for the school building and its grounds,
- cooperating with competent services (police, fire department, emergency medical services, civil protection) in the event of emergencies,
- participating in training and raising awareness among students and employees regarding safety protocols and emergency procedures,
- monitoring situations within school premises and reporting to the appropriate persons any behavior that could jeopardize the safety and well-being of students, employees, and visitors,
- cooperating with educational and other staff and the school principal to support the safety and well-being of students,
- performing other safety and civil protection tasks arising from the school's annual work plan and program and other regulations,
- potentially performing tasks specified in Article 6/8 of the Ordinance.

Regulations stipulate that the duties of an Operational Officer for Safety and Civil Protection in educational institutions may be performed only by persons who have completed the training program for acquiring the partial qualification of Operational Officer for Safety and Civil Protection in educational institutions. Exceptionally, these duties may also be performed by a person who has not completed the training program, provided they complete it within six months of the date of commencing employment in that position. [5]

2.4. Training Program for Operational Personnel in Security and Civil Protection

In March 2025, a Decision is adopted regarding the education program for acquiring the partial qualification of "Operational Staff Member for Safety and Civil Protection in Educational Institutions." Training for these positions is conducted based on this program. The program consists of the following **Sets of Learning Outcomes - SLO**[1] (10 CSVET credits)[2]:

[1] The term "Sets of Learning Outcomes" (SLO) corresponds to *Skupovi ishoda učenja* (SIU) in Croatian.

[2] CSVET stands for the Croatian Credit System for Vocational Education and Training. It is used within the Croatian vocational education system to express the student workload required to achieve specific learning outcomes and qualifications. Simply put, CSVET credits do not represent grades; rather, they measure the amount of work and time needed to master a specific module or set of learning outcomes. 1 CSVET credit represents 15 to 25 working hours required to achieve the corresponding learning outcomes. CSVET is used primarily in vocational schools and the vocational education system. In the new modular curriculum, each module is assigned a specific number of CSVET credits, indicating the student workload involved in instruction, work-based learning, independent study, and assessment. CSVET credits serve primarily schools, teachers, and the qualifications system for planning and recognizing learning outcomes, rather than for calculating school grades.

- SLO 1: Fundamentals of child and adolescent development at school age – 1 CSVET credit
- SLO 2: Basic communication skills and operational rules in educational institutions – 1 CSVET credit
- SLO 3: Protection duties and powers of the operational staff member for safety and civil protection in educational institutions – 6 CSVET credits[3]
- SLO 4: Fundamentals of technical protection, fire and explosion protection, and civil protection – 1 CSVET credit
- SLO 5: Fundamentals of self-defense and the use of coercive measures – 1 CSVET credit

SLO 3 is of particular importance within the Program, as it trains operational personnel on their powers and the methods for exercising those powers in the course of their duties. The powers of operational personnel as set out in the Program include:

- Issuing warnings and orders
- **Verifying the identity of persons**
- **Searching persons, objects, and vehicles**, and temporarily retaining or taking possession of objects
- Temporarily restricting freedom of movement
- Securing the scene of an incident
- Use of means of coercion – use of physical force, sprays containing harmless substances, batons, and restraining devices. [6] Powers provided for in the previously mentioned Protocol and the Regulations of April 2025 are marked in bold. Other powers derived from the Operational Staff Training Program are not listed in any regulation issued by the Ministry of Science, Education and Youth concerning safety in school institutions.

3. CHALLENGES IN THE IMPLEMENTATION OF THE OPERATIONAL STAFF ROLE

Operational security personnel face a range of challenges.

The most significant challenge is the lack of clear legal definitions regarding their status, professional standards, duties, powers, the manner in which those powers are exercised, and the procedures to be followed after exercising them—particularly following the use of coercive measures. The regulations establishing the role of Operational Security and Civil Protection Personnel address their duties and tasks only in a partial and generalized manner. Professional standards are barely mentioned. There is a need to clearly define the appearance, conduct, and visibility of these personnel. Should this involve a full or partial uniform, standardized equipment, or other necessary work tools? Uniforms and equipment should be identical across all schools; the only variation might be school-specific branding, such as a school emblem or logo. The operational staff member must be visible and easily noticeable. Amidst a crowd of students and other individuals, anyone requiring their assistance or support should be able to spot them quickly and easily and reach them.

[3] The SLO 3 was written by the authors of this article.

It is essential to clearly define the duties and powers of the operational security officer, the manner in which these powers are exercised, and the procedures to be followed after the exercise of any power—particularly following the use of coercive measures.

In the public (police) and private security sectors, duties, powers, the manner of their exercise, and post-action procedures are clearly defined by law.

Which regulation should an operational security officer cite when seizing a dangerous object from a student, parent, or other person? Or when detaining an individual and restricting their freedom of movement? Or when employing coercive measures—such as using a martial arts technique to restrain an individual attacking the officer, students, teachers, or others? To whom must the report be submitted, within what timeframe, and in what format or on which specific form? Who will assess the legality and justification of the use of coercive measures?

Within the public and private security systems, the answers to these questions are found in the law.

The public always reacts with caution and interest to the use of force by officials authorized to employ it. Through the education and training of police officers, the police force strives to uphold the highest standards regarding the use of force, ensuring that it is applied only as a last resort—lawfully and proportionately—and in a manner that minimizes harm to the individual against whom it is used.

Security personnel will employ authorized means of coercion in highly sensitive and specific settings—namely, educational institutions. These measures will be applied against any individuals present at or visiting such institutions who disturb public order and peace, behave violently, or commit misdemeanors or criminal offenses. At the moment of using force, the operational security officer must know and be certain that the means being used is lawful, that all legal conditions for its use have been met, that the use of force is lawful, and that the assessment of such use will be deemed justified and lawful. This will be achieved through clear legal provisions and continuous training regarding the performance of duties and tasks in the workplace.

The next set of challenges facing operational security personnel relates to their standing and status within school institutions.

They face a lack of acceptance—or insufficient acceptance—from school staff, parents, and others present in or entering school facilities A further challenge concerns the acceptance and recognition of the role of operational staff within school institutions. In practice, the role may not always receive adequate recognition from school management, with individual principals reportedly perceiving the position as unnecessary or as a measure introduced solely in response to the incident in Prečko. Such an approach overlooks the broader context of school safety and the existence of previous incidents of violence in Croatian schools. Effective implementation of the new safety system therefore requires clear recognition of the operational staff member as an integral part of the school's safety structure, together with clearly defined responsibilities and appropriate institutional support. The murder of a seven-year-old child is not an isolated incident. It is a criminal offense classified under Croatian criminal law as aggravated murder.

Security personnel must be at their posts during working hours—when students are in school and parents are visiting—remaining visible and ready to prevent disorder or violence, and to safeguard lives and property. They are not support staff for tasks such as hauling loads, taking out the trash, or

sourcing school supplies from shopping centers. The keyword defining their role is "security"; they represent the first operation level of preventive security within the school environment. They should be treated with due respect and provided with the necessary resources and workspace.

4. CONCLUSION

The introduction of operational staff for safety and civil protection in primary and secondary schools represents a justified and important step towards strengthening the safety and security of educational institutions. The establishment of this position should not be viewed solely as a response to an isolated incident, but as part of a broader effort to develop a systematic approach to the protection of students, employees, and other persons within school institutions.

The analysis presented in this paper indicates that the introduction of operational staff has established an important foundation for strengthening school safety. At the same time, several areas require further regulatory clarification and development. In particular, the legal basis for the exercise of individual powers, the conditions and procedures for their application, and the reporting, review, and accountability mechanisms following the exercise of such powers should be more precisely defined.

Further attention should also be given to establishing uniform professional standards, including the appearance, identification, equipment, and working conditions of operational staff. Continuous professional training should be ensured, particularly in the areas of communication, conflict management, self-defence, the use of coercive measures, emergency response, and cooperation with competent services.

The effective implementation of the operational staff role also requires their clear integration into the overall safety structure of school institutions. Their responsibilities and authority should be clearly understood by school principals, teachers, other employees, students, parents, and visitors. Institutional support and cooperation among all participants in the school community are essential for the effective performance of their duties.

Operational staff therefore represent an important element of the preventive safety system in schools. Their effectiveness, however, will depend not only on their training and individual competence, but also on the clarity of the regulatory framework, the consistency of its implementation, appropriate working conditions, and the support provided by school institutions and competent authorities.

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Professional paper

OCCUPATIONAL SAFETY AND HEALTH COSTS MANAGEMENT ACCORDING TO COST CENTRES

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***Abstract**: Identification and allocation of occupational safety and health costs are important components of contemporary sustainability accounting. In cost management is important to identify all relevant costs including occupational safety and health costs and allocate them according to the places of origin. In order to prevent losses resulting from accidents at work and occupational diseases, it is necessary to optimize investments in the safety and health of workers. Related to this, identification and allocation of occupational safety and health costs according to cost centres can help in managing costs and achieving better safety and health performance. Therefore, the main goal of the paper is to provide a proposal for identification and allocation of occupational safety and health costs according to cost centres. The proposal can help managers better understand occupational safety and health costs accounting, make easier decisions about safety and health investments, better control costs, achieve returns on investments, etc.*

***Key words**: occupational safety and health costs, cost management, cost centres, reporting*

1. INTRODUCTION

In a complex and uncertain business environment, cost management is the top priority for executives across industries. Cost management is an indispensable business practice with the aim of achieving the sustainability of business models. Sustainability challenges require cost management not only in terms of cost control but also in terms of predicting and optimizing costs. Accordingly, it is essential for the business to identify all relevant costs and allocate them according to the places of origin. One of the important cost groups is the cost of occupational safety and health (OSH). Identification and monitoring of OSH costs is necessary in order to more easily assess the risks for occurrence of costs arising from accidents at work, but also to plan costs that will contribute to improving health and safety at work and achieving benefits for both the enterprise and its stakeholders. Identification and allocation of OSH costs according to cost centres can prevent losses resulting from accidents at work and occupational diseases and help in managing costs and achieving better safety and health performance. Cost analysis by cost centres enables their

optimization, and further use for the calculation and internal reporting of OSH performance. Existing accounting systems of enterprises in Croatia often do not include an allocation of OSH costs, so the proposal for identification and allocaion of OSH costs according to cost centres could fill this gap.

2. OCCUPATIONAL SAFETY AND HEALTH COST MANAGEMENT

Given the necessity of constantly adapting business models to the challenges of modern business, cost management is a topic that continuously captures the attention of scientists and experts. Cost management involves comprehensive, systematic planning, control, and analysis of costs throughout the business process to help minimize costs and maximize benefits (Chang, 2024). The effective cost management is undoubtedly the key to the successful performance of the enterprise (Mesároš et al., 2015). The basic postulate of cost management can be described as "the achievement of managerial goals with the optimal cost engagement" (Belak, 1995). Accordingly, the achievement of management goals implies the optimal engagement of all costs, including the costs of occupational safety and health (OSH). Safety cost optimization aims to determine the optimal safety strategy with minimal costs from all the safety investment strategies (Chen et al., 2021). Understanding OSH costs is crucial for decision-making processes, especially for prioritizing preventive measures as well as realizing financial benefits for enterprises. Previous research clearly distinguishes two fundamental groups of OSH costs: preventive (planned, targeted) costs versus corrective (unplanned, consequence) costs. Preventive costs are the result of a proactive approach to the OSH management and are aimed at preventing accidents at work and worker illnesses (Krivačić, Špehar, 2024). Preventive OSH costs include investments in the safety of working conditions, protective equipment, education, preventive health examinations of workers, costs of managing OSH systems, etc. On the contrary, the costs incurred as a consequence of accidents at work and occupational diseases of workers represent the costs that were not incurred on purpose, but as a consequence of an adverse event. These costs include the costs of overtime work due to the compensating the injured worker's working hours, fines and compensation, as well as expenses arising from reduced productivity, frequent fluctuations of workers, absenteeism, etc. OSH cost management aims to predict the occurrence of corrective OSH costs, which requires optimization of preventive costs, i.e. costs of improving OSH performance. Companies investing in occupational safety and health programmes obtain tangible results such as a reduction in costs arising from absenteeism, reduction in staff turnover, greater customer satisfaction, increased motivation, improved quality and enhanced company image (EC, 2011). The spending on occupational safety and health is an investment that "pays off" for companies and the return on prevention is assessed to be 2.2 (1€ spent yields 2.2€) (ISSA, 2013). Research conducted by Mustard and Yanar (2023) found a return of employers' OSH expenditures ranging 1.24 to 2.14 monetary units. Returns on OSH investments most often manifest as hazard reduction, increased awareness of hazards, reductions in dangerous behaviour and accidents, as well as improved company image and company culture (ISSA, 2011). Initially, investments in preventive OSH activities can be considerable and increase total costs, but additional investments can reduce future costs. Some estimates are that interventions appeared to be economically beneficial within the five-year period examined, because of increased productivity or lower costs (EU-OSHA 2014). Investments in OSH contribute not only to enhanced wellbeing for workers and entrepreneurs but also to high returns, particularly in terms of cost reduction, greater productivity and sustainability of social security systems (EESC, 2019). Generally, all forms of OSH activities impact on the quantity, quality and effectiveness of human capital and contribute

to business performance (EU-OSHA, 2024). Therefore, adopting appropriate cost management concept is unavoidable starting point. In the context of limited resources (and this is always the context), it is useful to know where the most substantial costs are located (Dorman, 2000). Cost management according to cost centres is one of the management methods for capturing, monitoring and controlling costs as well as for their easier forecasting and budgeting. Cost centres represent functions, departments, teams, or any other enterprise's unit where costs are incurred. They are managed by the persons responsible for certain unit within the enterprise, which makes it easier to identify and optimise them. OSH cost management according to costs centres can accurately allocate OSH expenses, monitor OSH financial performance and control OSH costs.

3. ALLOCATION OF OCCUPATIONAL SAFETY AND HEALTH COSTS ACCORDING TO COST CENTRES

When developing proposal for the allocation of OSH costs according to cost centres, the authors decided to place emphasis on preventive OSH costs. The allocation of preventive OSH costs is carried out by including them in the accounting information system of an enterprise. For their identification, recording, analysis and reporting it is necessary to provide groups of accounts within the chart of accounts.

The following is a proposal of the process of allocating OSH costs using the example of an enterprise in Croatia. The process begins with identifying the types of OSH costs. According to the criterion of natural cost types, occupational safety and health costs can be recorded in two main groups:

- material costs (group 40 according to the chart of accounts), i.e. protective equipment and safety supplies,
- service costs (group 46 according to the chart of accounts), i.e. training, inspections, outsourced safety services, medical examinations.

In the following sections, it will be shown how to track personal protective equipment costs by cost centres, i.e. how to allocate them to each individual department within enterprise. The examples are based on the Croatian accounting and tax framework and the account codes represent the authors' own proposal. Table 1 shows the basis for recording costs according to cost centres, i.e. examples of departments within a particular enterprise which can be separate cost centres. The table lists several main cost centres, namely: production, maintenance, procurement, sales, and administration. Each department is tracked under a separate code, which the enterprise can define internally, depending on its accounting policies. The department codes in the table below are a proposal by the author.

Table 1: Departments

Code	Department
100	Production
101	Maintenance
102	Procurement
103	Sales
104	Administration

In order to explain the allocation of OSH costs to cost centres, in the following two examples are simulated business events that initiate the classification of costs to cost centres.

Example No. 1

Enterprise XY received an invoice for protective helmets in the amount €400.00 + VAT. The helmets were purchased for production purposes, and it was decided that the cost would be allocated to the production department (100). The net amount €400.00 is recorded to account 4005 – Personal protective equipment, the VAT expense is recorded to account 1400 – Input VAT on received invoices, and the total invoice amount is recorded to account 2200 – Liabilities to suppliers. Account 4005 needs to be assigned to cost centre, i.e. the cost must be allocated to the place where it actually occurred.

Table 2: Example of journal entries - personal protective equipment

Account	Code	Description	Debit	Credit	Date	Cost centre	Cost centre name
4005	-	Protective helmets	400,00	0,00	May 4, 2026	100	Production
1400	-	VAT	100,00	0,00	May 4, 2026	-	-
2200	24	Supplier XY	0,00	500,00	May 4, 2026	-	-

Example No. 2

The enterprise has hired four new employees. Two in the sales department, one in the administration department and one in the maintenance department. The enterprise paid for a medical examination for each of them. It has received an invoice in the amount of €**320.00 + VAT** for performed medical examinations. It is necessary to allocate the cost across departments. The cost of a medical examination per person is €80.00, so accordingly €160.00 will be allocated to the sales department (103), €80.00 to the maintenance department (101), and €80.00 to the administration department (104). Below is a presentation of the journal entries for the above example.

Table 3: Example of journal entries - medical examination

Account	Code	Description	Debit	Credit	Date	Cost centre	Cost centre name
4695	-	Medical examination	160,00	-	May 4, 2026	103	Sales
4695	-	Medical examination	80,00	-	May 4, 2026	101	Maintenance
4695	-	Medical examination	80,00	-	May 4, 2026	104	Administration
1400	-	VAT	80,00	-	May 4, 2026	-	-
2200	32	Supplier XY	-	400,00	May 4, 2026	-	-

Enterprises that have production halls must ensure that they are properly marked. They must have warning signs (e.g. high voltage), prohibition signs (e.g. no smoking), mandatory signs requiring the use of protective helmets, a clearly marked exit, evacuation routes, etc. In order to meet the prescribed requirements, if they do not have a separate occupational health and safety department, they must hire specialized experts in this field. In that case the enterprises should record all costs of

external associates specialized in occupational health and safety on a separate account and by cost centres. It is also necessary to mention employee training in accordance with occupational health and safety regulations and rules. Each employee should complete occupational health and safety training prescribed for his or her job position. For OSH training is necessary to engage a specialist, and this cost should likewise be recorded on a separate account and allocated to specific cost centre.

4. INTERNAL REPORTING OF OCCUPATIONAL SAFETY AND HEALTH COSTS ACCORDING TO COST CENTRES

Every cost related to OSH should be recorded and accounted for in the previously presented manner, so management can ensure effective and high-quality workplace protection. Management should plan OSH costs, monitor their share in total expenses, and review their overall trends. This also include internal reporting. Each enterprise should tailor its internal reports to its own needs. Several examples can be provided to illustrate what the reports should look like and what they should include. Table 4 shows an example of internal report of OSH costs allocated to cost centres. The table includes the amount of OSH costs by departments, the share of these costs in total material costs, personnel costs, and other expenses. It also shows the relationship between the planned budget for OSH costs, allowing management to assess whether planning was realistic and how much funding was actually spent. Likewise, the table can contain comparison data for the current year and the previous year.

Table 4: Example of report

Account	Expense name	Planned 2026 (€)	Difference between actual and planned	Actual 2025 (€)	INDEX (previous year/ current year) %	Share in total costs (%)
4005	Personal protective equipment					
4695	Medical examination					
4696	Systematic medical examinations					
411	Services of external occupational health and safety experts					

Such a report can be prepared for each individual department in order to identify the amount required by each department to ensure OSH. The report should contain all the elements necessary for management to properly plan and organize OSH costs. In addition to internal reporting enterprises should also monitor the frequency of workplace injuries. Although it is assumed that workplace injuries will occur most frequently in production departments, they should be monitored at the level of the entire enterprise and correlated with the costs of investing in proper OSH measures. For example, the cost of workplace injury can be calculated by multiplying the lost working hours by the average gross hourly wage for each individual department. Table 5 presents the proposal how to relate the quality of implementing occupational health and safety measures by departments to the cost of workplace injuries incurred during a specific period.

Table 5: Analysis of total occupational health and safety costs and working injury costs

Code	Department	Costs of implementing occupational health and safety measures (2026)	Costs of workplace injuries (2026)
100	Production		
101	Maintenance		
102	Procurement		
103	Sales		
104	Administration		

5. CONCLUSION

Besides being mandatory for enterprises investment in occupational safety and health is also a factor of business success and sustainability. As a component of contemporary cost management and management accounting allocation of OSH costs according to cost centres is important to prevent risks and losses resulting from accidents at work and occupational diseases. Previous research has found that it pays for enterprises to invest in OSH. Therefore, the proposal for identification and allocation of OSH costs according to cost centres, presented in this paper, may help managers better understand OSH costs accounting. The proposal may support management decision-making about OSH investments and control of OSH costs as well as evaluating returns on OSH investments. It provides a basis for further practical validation.

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Research article

PHYSICAL FOUNDATIONS OF A RADIOLOGICAL AND NUCLEAR DISASTER

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***Abstract**: Radiological and nuclear disasters represent complex events in which physical processes determine the extent of damage and patterns of population exposure. The fundamental physical principles relevant to understanding such events are presented. Emphasis is placed on the law of radioactive decay and half-life as key tools for assessing the duration of hazards. The dispersion of radionuclides through air, water, and soil is also considered, with a distinction between contamination and irradiation, as well as between external and internal exposure. Understanding physical laws is necessary for timely decision-making in population protection and the organization of medical response under conditions of radiological and nuclear incidents.*

***Keywords:** radiological disasters; nuclear disasters; ionizing radiation; radioactive decay; contamination*

1. INTRODUCTION

The basic characteristic of radiological and nuclear disasters is the presence of ionizing radiation. An adequate assessment of risk, together with the planning of response measures and the medical management of injured persons, must be grounded in an understanding of the underlying physical processes and the effects of ionizing radiation on matter and living organisms.

The transfer of energy through space or matter in the form of electromagnetic waves or particles is called radiation. Radiation can be divided into ionizing radiation and non-ionizing radiation. The difference lies in their effects on matter and living organisms. Non-ionizing radiation, due to insufficient energy, does not eject electrons bound to atoms or molecules. It only causes excitation of electrons in the atom and vibrations of molecules in the matter on which it acts. In contrast, ionizing radiation has sufficient energy to eject a bound electron from atoms or molecules and thereby cause ionization of matter.

2. NUCLEAR REACTIONS AND RADIOACTIVITY

When two atomic nuclei collide, changes in their structure may occur, during which mass decreases and energy is released. Part of the mass is converted into energy according to Einstein's formula $E=mc^2$. Such processes are called nuclear reactions. The energy released in a nuclear reaction is approximately one million times greater than the chemical energy released in a chemical reaction. Nuclear reactions occur if a nucleus (projectile nucleus) strikes another nucleus (target nucleus) or when a neutron strikes the target nucleus. In both cases, a change in the structure of the nucleus and the release of energy occur.

The emission of energy by means of electromagnetic radiation or particles may also occur spontaneously, i.e., without collision processes as in nuclear reactions. Radioactive decay is any process in which an atomic nucleus changes spontaneously, without external influence. In some radioactive processes the nucleus only loses energy but does not change its structure, whereas in others it also changes its structure.

2.1 Gamma Radiation

Each atomic nucleus can exist in one of its energy states. Energy states may be the ground state (minimum energy), the first excited state, the second excited state, and so forth, similarly to how electrons can be excited in the electron shell. Physical systems spontaneously transition to more stable states, states of lower energy, which means that an excited nucleus will also transition to a state of lower energy. During the transition from an excited state to the ground state, the nucleus emits a photon whose energy is equal to the difference between the energies of the initial and final states. In the process of photon emission, the energy of the nucleus decreases, while its structure does not change. This process is called gamma radiation, and the energy carried by photons is about one million times greater than the energy carried by photons emitted by atoms. Due to their high energy, gamma-radiation photons are highly penetrating; they damage the shells of atoms and molecules with which they collide and have a destructive effect on the tissues of living beings.

2.2 Alpha Decay

Some radioactive nuclei spontaneously emit two protons and two neutrons in the form of a helium nucleus. Such a process is called alpha decay. In this process, a daughter nucleus and a helium nucleus are formed from the parent nucleus.

2.3 Beta Decay

Some unstable nuclei spontaneously change their structure so that one neutron in them is converted into a proton or one proton into a neutron. Such a process is called beta decay. It is evident that there are two beta decays, beta-minus and beta-plus decay.

In beta-minus decay, a neutron in the nucleus decays, while two particles, an electron and an antineutrino, are emitted from the nucleus. In beta-plus decay, one proton in the nucleus is converted into a neutron, while an antielectron (positron) and a neutrino are emitted from the nucleus. In both decays, a change in the structure of the nucleus has occurred, i.e., from the parent nucleus we obtain a daughter nucleus with the emission of an electron and an antineutrino or of a positron and a neutrino.

3. EFFECTS OF IONIZING RADIATION ON HUMANS

If a substance is under the influence of ionizing radiation, an increase in the energy of atoms and molecules in that substance occurs. It can be said that the amount of absorbed energy is important for how radiation acts on a substance. As a particle of radioactive radiation passes through a substance, positive ions and free electrons are formed along its path. The number of ions formed per unit length of path is called specific ionization. Specific ionization depends on the type of radiation; it is greatest for alpha radiation, lower for beta radiation, and lowest for gamma radiation. When passing through matter, gamma radiation loses energy most slowly and is therefore highly penetrating. Because of its “size”, alpha radiation has high specific ionization and therefore its range in tissue is very small. When it strikes the human body externally, the skin absorbs it completely and it does not reach the internal organs. A similar statement also applies to beta radiation. However, if an alpha- or beta-radioactive substance is introduced into the organism through food, drink, or inhalation, then these types of radiation act destructively on the internal organs.

In addition to absorbed energy, which is associated with the absorbed dose, the equivalent dose also plays a very important role. The equivalent dose represents a measure of the biological effect of ionizing radiation on biological tissue. In addition, exposure may also be mentioned for X-ray and gamma radiation.

The effective dose represents the total effect of radiation on the entire organism. It must be taken into account that different organs and tissues are not equally sensitive to radiation. The effective dose provides a single measure that describes the total biological effect of radiation on humans, regardless of where the radiation was absorbed. This enables comparison of different situations of exposure to radiation.

Risk assessment is based on the relationship between the received dose and the probability of harmful consequences, primarily the development of malignant diseases. The greater the dose, the greater the probability of damage, although the effects do not necessarily appear immediately. Precisely for this reason, in radiological and nuclear accidents efforts are made to assess the level of exposure as quickly as possible so that protective measures can be taken in a timely manner and the long-term risk to the population can be reduced.

4. RADIOLOGICAL AND NUCLEAR DISASTERS – DISPERSION AND EXPOSURE

In radiological and nuclear disasters, radioactive substances are released and may spread through the environment by means of air, water, and soil. Dispersion depends on physical conditions such as wind, precipitation, and relief, so contamination may affect large areas. It is important to distinguish between irradiation and contamination. Irradiation occurs when a person is exposed to a radiation source without necessarily having contact with a radioactive substance. Contamination means the presence of radioactive particles on the surface of the body, in the environment, or inside the organism. Internal contamination is particularly dangerous because incorporated radioactive substances may irradiate from within for a long time and damage tissues. Understanding these processes enables the proper implementation of protective measures, such as evacuation, decontamination, and restrictions on the intake of contaminated food and water. In radiological and nuclear disasters, released radionuclides spread through the environment by means of air,

water, and soil, and their movement is determined by physical and meteorological conditions. In the atmosphere, radionuclides are transported by wind and may be deposited on the ground by dry or wet deposition, especially during precipitation. Once they reach the soil, they may bind to particles, penetrate into deeper layers, or enter the food chain. In aquatic systems, radionuclides may dissolve, be transported by currents, and accumulate in sediments or living organisms.

Under such conditions, a distinction is made between external and internal exposure to radiation. External exposure occurs when the organism is exposed to a radiation source from the environment, without the intake of radioactive substances into the body. Internal exposure occurs through the intake of radionuclides into the organism by inhalation, food, or water, whereby they may irradiate from within for a long time. It is precisely internal contamination that often represents a longer-lasting and more difficult-to-control risk. The law of radioactive decay is used to describe the change in radionuclide activity over time. The number of unstable nuclei decreases exponentially with time, which means that the activity of the source gradually decreases. Half-life represents the time in which the number of radioactive nuclei decreases to one half of the initial value. This parameter is essential for assessing the duration of hazards and planning protective measures. The combination of radionuclide dispersion and their decay determines the actual level of exposure and the total risk to the population. Radiological and nuclear disasters represent complex events in which physical processes determine the origin, dispersion, and effects of ionizing radiation. Understanding the structure of the nucleus, radioactive decay, and the interaction of radiation with matter enables a quantitative assessment of exposure and consequences for humans and the environment. It is particularly important to distinguish between external and internal exposure and to understand the role of different types of radiation in the development of damage to biological tissue.

In the context of mass-casualty accidents, physical models of radionuclide decay and transport form the basis for contamination assessment, planning of protective measures, and medical response. Therefore, physical laws do not represent only a theoretical foundation. They are a key tool in the management of radiological and nuclear incidents.

5. CONCLUSION

Understanding physical processes constitutes the basis for risk assessment in radiological and nuclear disasters. Ionizing radiation causes the ionization of matter and biological tissues, and the type of radiation determines both its penetration and the degree of biological damage. The effective dose enables assessment of the total biological effect of radiation on the organism and allows comparison of different exposure situations. The dispersion of radionuclides through air, water, and soil is determined by physical and meteorological conditions and represents a key factor in the extent of contamination. It is therefore necessary to clearly distinguish between irradiation and contamination, as well as between external and internal exposure, with internal contamination often representing a longer-term risk. The law of radioactive decay and half-life are essential for assessing the duration of hazards and planning protective measures. Physical models of radionuclide dispersion and decay consequently enable timely decision-making in population protection and in the organization of medical response.

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Professional paper

THE EFFECTS OF IRREGULAR MIGRATION ON THE ECONOMY AND SUSTAINABLE DEVELOPMENT: ECONOMIC AND SAFETY IMPLICATIONS

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Abstract: *This paper examines the effects of irregular migration on the economy and sustainable development, with particular emphasis on its economic and security implications. The study analyses the short-term challenges that irregular migration may pose to national budgets, social welfare systems, and public security. Increased pressure on public services, border management, housing, healthcare, and law enforcement can generate significant fiscal and administrative burdens, especially in countries facing large and sudden migration inflows. At the same time, the paper explores the long-term opportunities that can emerge when migration is managed responsibly and strategically. In particular, migration can help address demographic decline, labour shortages, and broader development needs. The paper further considers whether current European Union migration policies are effective, fair, and sustainable in responding to these complex challenges. It argues that a balanced approach is needed—one that strengthens security and institutional capacity while also promoting legal pathways, integration, and long-term socio-economic resilience.*

Keywords: *irregular migration, economy, sustainable development, safety, migration policy*

1. INTRODUCTION

International migration has become one of the most important demographic, economic, and political challenges facing the European Union. Geopolitical conflicts, economic disparities, climate change, and humanitarian crises have intensified migration flows, increasing pressure on national institutions and raising questions regarding the sustainability of current migration policies [1,14].

Although migration contributes to economic growth, labour mobility, and cultural diversity, irregular migration creates additional challenges because it occurs outside established legal and institutional frameworks. Large and unmanaged migration flows may increase expenditure on border protection,

asylum procedures, healthcare, housing, education, and social welfare while simultaneously encouraging informal employment and reducing public revenues [19, 2]. At the same time, migration should not be viewed exclusively as a security concern. Population ageing, declining fertility rates, and persistent labour shortages have increased the importance of migration for maintaining economic competitiveness and supporting sustainable development within the European Union. Consequently, the principal policy challenge is to reduce irregular migration while expanding legal migration pathways and strengthening integration policies.

This paper analyses the demographic, economic, socio-cultural, and political effects of irregular migration, with particular emphasis on their implications for sustainable development in the European Union. Special attention is given to the relationship between migration governance, economic sustainability, and institutional resilience.

The study adopts a combined quantitative and qualitative research approach based primarily on secondary data and desk research. The quantitative analysis draws on statistical data from Eurostat, Frontex, the European Union Agency for Asylum (EUAA), the OECD, and UNHCR, including data on irregular border crossings, asylum applications, demographic trends, and selected socio-economic indicators. The qualitative component comprises an analysis of relevant EU legislation, migration and asylum policy documents, institutional reports, and scientific literature. The collected data and documents were examined using descriptive, comparative, analysis and synthesis methods, enabling the identification of key migration trends and differences among EU Member States.

This methodological approach provides a comprehensive framework for assessing both the immediate challenges associated with irregular migration and its broader implications for the long-term economic, social, and institutional sustainability of the European Union.

2. THEORETICAL BACKGROUND OF MIGRATION AND SUSTAINABLE DEVELOPMENT

Migration is a multidimensional phenomenon that influences demographic change, economic development, labour markets, and public policy. According to the International Organization for Migration [15], migration refers to the movement of persons across or within national borders regardless of legal status, duration, or causes. A distinction is generally made between regular migration, which complies with national legislation, and irregular migration, which involves entry, residence, or employment outside legal migration frameworks [2].

Several theoretical approaches explain migration dynamics, reflecting the complexity of factors that influence migration decisions and patterns. The neoclassical economic theory focuses primarily on economic motivations and argues that migration results from wage differentials and employment opportunities between countries [12]. However, economic differences alone cannot fully explain contemporary migration flows. A broader perspective is therefore provided by the push-pull approach. Lee's (1966) push-pull theory explains migration through factors that drive individuals from their countries of origin, such as poverty, conflict, and unemployment, and factors attracting them to destination countries, including higher incomes, political stability, and better living conditions [16].

In addition to individual and economic motivations, social relationships play an important role in maintaining migration flows over time. Migration network theory emphasises that family and social networks reduce migration costs and facilitate continuing migration flows [17]. While these

approaches focus mainly on individual decisions and social relationships, structural theories examine migration within the broader context of global economic inequalities. Wallerstein (1974) argues that the expansion of the capitalist world economy creates structural inequalities between core and peripheral regions, which can contribute to international labour mobility [22].

Taken together, these theoretical perspectives demonstrate that migration cannot be explained by a single factor. Rather, it results from the interaction of economic, social, political, and structural conditions, while its consequences extend to both countries of origin and destination. Migration processes can have far-reaching demographic and socio-economic consequences, particularly for countries experiencing population decline, labour shortages, and the emigration of younger population groups [15].

These demographic and socio-economic implications also provide an important link between migration and sustainable development. The United Nations 2030 Agenda recognises well-managed migration as an important contributor to economic growth, reduced inequalities, and inclusive societies, particularly through SDGs 8, 10, 11, and 16 [20]. Accordingly, SDG Target 10.7 calls for safe, orderly, and responsible migration through well-managed migration policies. From this perspective, migration governance becomes an integral part of achieving long-term economic and social sustainability.

Within the European Union, migration governance seeks to balance humanitarian responsibilities with economic competitiveness and security concerns. Demographic ageing and labour shortages have increased the importance of legal migration, while irregular migration continues to challenge border management, asylum systems, public finances, and social integration [2, 3, 9, 19]. This dual character of migration—as both a potential contribution to sustainable development and a challenge for institutional and security systems—provides the basis for analysing the effects of irregular migration in the following sections.

Figure 1 illustrates that legal migration has consistently exceeded irregular migration in the European Union during the period 2013–2023. Although irregular migration attracts considerable political attention, it represents only a relatively small proportion of overall migration flows. This finding supports a more evidence-based understanding of migration trends and contributes to more balanced policy discussions [8,11].

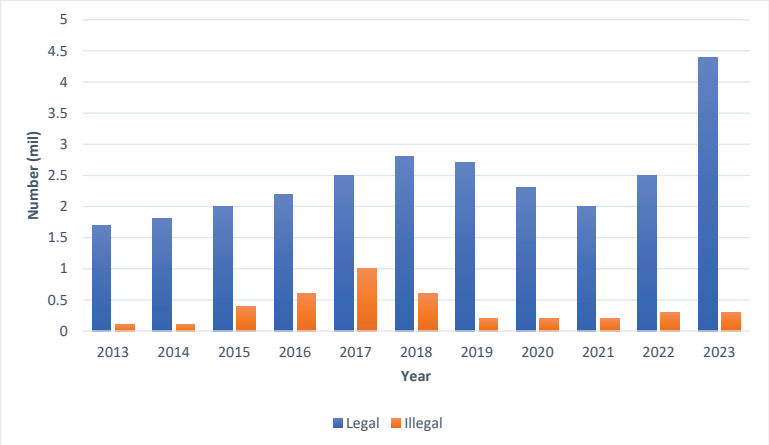


Figure 1. Legal and Irregular Migration in the European Union (2013–2023)

Source: Authors' own elaboration based on data from Eurostat (2023), Frontex (2024), and the European Commission's Migration Statistics (2013–2023)

3. THE EFFECTS OF IRREGULAR MIGRATION ON SUSTAINABLE DEVELOPMENT

Irregular migration has significant implications for the demographic, economic, social, and institutional sustainability of the European Union. Although migration presents considerable challenges for border management and asylum systems, it also interacts with long-term demographic change and labour market needs, making effective migration governance an essential component of sustainable development [1, 19].

3.1. Demographic Effects

The European Union has experienced persistent population ageing, declining fertility rates, and a shrinking working-age population for several decades. According to Eurostat [9], by 2050 almost one-third of the EU population will be aged 65 or over, placing increasing pressure on pension systems, healthcare, and economic productivity. Most irregular migrants are young adults. Frontex [11] and IOM [14]. report that more than 60% belong to the 20–49 age group, representing a potential source of labour in countries experiencing workforce shortages. Member States such as Italy, Croatia, Bulgaria, and Latvia already face declining populations and labour deficits in sectors including construction, agriculture, hospitality, logistics, and elderly care [19].

However, the demographic benefits of migration depend largely on successful integration. Irregular migrants frequently experience restricted access to formal employment, education, healthcare, and social protection, increasing the risk of social exclusion and limiting their contribution to long-term economic development [7, 13].

According to the MIrreM Project [18] between 2.6 and 3.2 million irregular migrants reside in twelve European countries. Although this represents less than 1% of the total EU population, their long-term contribution depends on effective migration governance, legal migration pathways, and labour market integration.

3.2. Economic Effects

Irregular migration has important economic consequences, particularly in sectors characterised by persistent labour shortages, including construction, agriculture, hospitality, logistics, and long-term care [20]. Although much of this employment occurs within the informal economy, irregular migrants often perform jobs that are difficult to fill with the domestic workforce, thereby supporting production and local consumption. At the same time, undeclared employment, labour exploitation, unfair competition, and the absence of tax and social security contributions reduce public revenues and distort labour market conditions [1, 13]. Consequently, irregular migration may increase the size of the informal economy and create long-term fiscal challenges for Member States. Public expenditure associated with irregular migration includes border management, asylum procedures, return operations, emergency accommodation, healthcare, and law enforcement. The overall fiscal impact varies considerably according to the scale of migration flows, administrative efficiency, and national migration policies [4].

Despite these challenges, migration should not be viewed solely as an economic burden. Given Europe's ageing population and increasing labour shortages, well-managed migration can contribute to economic resilience, labour market stability, and sustainable development. The principal challenge is therefore to strengthen legal migration channels while reducing irregular migration and improving labour market integration [1, 19].

3.3. Socio-Cultural Effects

The effects of irregular migration extend beyond economic indicators and influence the social, cultural, and institutional development of host societies. While migration contributes to cultural diversity and demographic renewal, large and unmanaged migration flows may challenge social cohesion, public services, and integration processes [19,14]. Regions experiencing higher concentrations of irregular migrants often face increased demand for education, healthcare, housing, and social welfare services. Schools require additional language support and integration programmes, while healthcare systems and local authorities experience growing pressure on their administrative and financial capacities [4]. Nevertheless, research indicates that these pressures depend primarily on the effectiveness of migration governance, labour market participation, and integration policies rather than migration itself [1, 21].

Public attitudes towards migration are also shaped by political discourse, media representation, and perceptions of security. Consequently, successful integration policies remain essential for strengthening social cohesion and reducing social tensions within increasingly diverse European societies [14].

3.4. Political Effects

Irregular migration has become one of the most politically sensitive issues within the European Union. Although irregular migrants account for only a small proportion of the total EU population, migration frequently dominates political debate, particularly during election campaigns [2,14]. Political responses differ considerably among Member States. While some governments emphasise solidarity, international protection, and human rights, others prioritise border security, return procedures, and the protection of national interests [3]. These differences continue to complicate the development of a common European migration policy despite the adoption of the New Pact on Migration and Asylum [5].

Between 2020 and 2024, migration pressure was distributed unevenly across the European Union. Italy, Greece, and Spain remained the principal entry points along the Mediterranean routes. Italy recorded more than 150,000 irregular arrivals in 2023, while Greece registered over 70,000 arrivals, primarily through its land and maritime borders with Türkiye. Spain experienced a substantial increase in arrivals through the Canary Islands, creating additional pressure on local reception capacities [10, 1, 2]. Cyprus represented the most affected Member State relative to its population size, recording approximately 13 asylum applications per 1,000 inhabitants, highlighting the vulnerability of smaller countries with limited institutional capacity [6, 8]. Germany remained the largest destination country for asylum seekers, receiving more than 329,000 asylum applications in 2023, representing almost one-third of all applications submitted within the European Union [6]. Many migrants continue through secondary movements from frontline states towards economically stronger Member States, placing additional pressure on asylum systems and integration policies [19].

These regional differences demonstrate that migration pressure depends not only on the number of arrivals but also on geographical location, institutional capacity, and national migration policies. Consequently, strengthening European solidarity, improving responsibility-sharing mechanisms, and implementing effective migration governance remain essential for ensuring the long-term sustainability of the Common European Asylum System [1,3].

4. CONCLUSION

Irregular migration represents one of the most complex and multidimensional policy challenges facing the European Union, with implications for demographic development, labour markets, public finances, social cohesion, institutional capacity, and security. The analysis presented in this paper demonstrates that its effects extend well beyond border management and cannot be adequately addressed through restrictive or security-oriented measures alone. Instead, irregular migration requires an integrated policy response that combines effective migration governance, economic and social sustainability, institutional resilience, and respect for fundamental rights.

The findings reveal a clear dual dimension of migration. In the short term, irregular migration can generate additional fiscal and administrative pressures related to border control, asylum procedures, reception, healthcare, housing, and social services. These pressures are particularly pronounced in Member States located along the EU's external borders and in countries experiencing sudden increases in arrivals. At the same time, Europe's ageing population, declining working-age population, and persistent labour shortages demonstrate the growing importance of migration for the long-term functioning of European economies. The potential economic and demographic benefits of migration, however, depend on the ability to channel migration into legal pathways and ensure effective labour market and social integration. The analysis also confirms that migration pressure is distributed unevenly across the European Union. Geographic location, institutional capacity, and the attractiveness of individual labour markets create different challenges for frontline and destination countries. This imbalance underlines the importance of European solidarity, effective responsibility-sharing, and stronger coordination between Member States. The sustainability of the common European migration framework will therefore depend not only on controlling external borders but also on the capacity of the EU to respond collectively to changing migration patterns.

From the perspective of sustainable development, the central challenge is therefore not simply how to reduce irregular migration, but how to manage migration in a way that transforms potential pressures into long-term social and economic benefits. A sustainable approach should combine effective border management and measures against migrant smuggling with efficient asylum procedures, expanded legal migration pathways, labour market integration, and cooperation with countries of origin and transit. Such an approach is consistent with the broader objectives of the 2030 Agenda, particularly the principle of safe, orderly, and responsible migration. Ultimately, migration policy should seek a balance between security, solidarity, and sustainability. Strengthening institutional capacity while creating realistic opportunities for legal migration and integration can reduce the negative effects associated with irregular migration and allow migration to contribute more effectively to Europe's demographic and economic resilience. In this sense, the long-term success of EU migration policy will depend on its ability to move beyond short-term crisis management towards a coherent, evidence-based, and sustainable migration governance framework.

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Professional paper

THE PROPOSAL OF A LEGAL FRAMEWORK ON EQUIPMENT SAFETY USED IN AMUSEMENT PARKS

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Abstract: *In recent years, there has been an increase in accidents in amusement parks in Serbia. The safety of the equipment used in these parks is not regulated by legislation in the Republic of Serbia, not only in the phase of design and manufacture, but also in operation, maintenance, and use, as well as when it comes to requirements for inspection during design, manufacture, operation, and use.*

The rides and devices used in amusement parks are, in fact, machines. Still, they are not subject to the Machinery Safety Directive (2006/42/EC), which is implemented in the Bylaw on Machinery Safety (Official Gazette, no. 58/2016 and 21/2020). The safety of this equipment is regulated by a set of standards. Experts state that, although accepted, these standards do not have an obligatory character, but are instead more of a suggestion. Therefore, we consider it necessary to enact mandatory legislation on amusement park equipment safety. This paper proposes a safety framework for amusement park machinery.

Keywords: *amusement parks, machinery safety, equipment inspection, maintenance*

1. INTRODUCTION

An amusement device is an arrangement of equipment that produces the desired effect of amusement or entertainment when the passenger moves through it or on it primarily by his or her own action, or any other system that is not covered by the term amusement ride. Equipment designed to entertain passengers during motion, including the biomechanical effect, is at the same time an amusement ride. Although equipment and devices integrated in amusement parks are not subject to the Machinery Safety Directive (1), the European Committee for Standardization regulated this field with a set of standards. These standards were established in 2019 (2,3,4), and they deal with the safety of amusement rides and amusement devices. Standards are adopted in the Republic of Serbia by the Institute for Standardization of Serbia. There are three parts of these standards which refer to design and manufacture, operation, maintenance and use, and requirements for inspection during design, manufacture, operation and use. Similar to the requirements of the Machinery Safety Directive, there are also requirements for design analysis, design documents, design risk assessment, and many more things related to the safety of these devices.

However, these standards do not have a mandatory character, but are only accepted as a form of recommendation. After several accidents with serious injuries occurred in previous years, it is obvious that the reaction of the relevant institutions is necessary.

During the fair, the structural part of the carousel collapsed in Kuršumlija, Republic of Serbia, causing 13 people (mostly children) to be injured, and a girl (12) was more seriously injured in September 2024. Several visitors were injured due to parts of the equipment on the fair's merry-go-rounds being detached in Svilajnac in 2024 and Ugrinovci in 2025.

The investigation established that all of this equipment was homemade and not manufactured in accordance with contemporary standards. Therefore, it can be clearly seen that procedures that would ensure the safety of users were not conducted. Thus, stricter control of the equipment used in amusement parks is required, both in the design and production phase, as well as in the exploitation phase.

2. DESIGN AND MANUFACTURING

The design documents include all the documents required for the assessment of the stability and operational safety of the amusement device, including the Design Risk Assessment DRA). They shall be available for any subsequent approval by independent inspection bodies. These documents should encompass all the design conditions about the operation of the amusement devices or structures. A description of the construction, operation, and operational safety, design drawings, and comprehensive stress, fatigue, and stability analysis are required for this purpose. The design and manufacturing phase of amusement park devices requires recognition of the main hazards, hazardous situations, and events for spectators and passengers during the operation and use of amusement rides. Mechanical hazards (including hazards due to motion of passengers on rides), electrical, acoustic, ergonomic, hazards of abnormal situations, hazards from human actions, hazards arising from lack of information, as well as hazards associated with the environment in which the ride is used should be carefully considered in this phase.

Mechanical hazards originate from intensity and duration of accelerations and jerks, excessive speed, emergency state, and bad design and construction. Effects can be hazards arising from the intensity and duration of forces exerted by elements of the passenger containment, speed and acceleration; injury by projectiles; problems of emergency egress as a result of pinch points and inadequacy of mechanical-structural strength. Potential consequences could be crushing, cutting or severing, discomfort, motion sickness, musculoskeletal disorder, ejection of passengers. Also, crushing, stabbing, or puncture can be caused, as well as difficult access for emergency services. Bad design or construction can potentially result in loss of strength, structural and mechanical failures, and loss of stability.

Electrical hazards originate from bad design or construction, environmental agents, and bad components. This could manifest as component crashes and perturbations, and as a potential consequence, failure and disorder in the control system can occur.

Acoustic hazards mostly refer to the noise sources and could cause improper operator error and prevent the public or passengers from hearing the alerts.

Ergonomic hazards originate from posture, seat, and inadequate consideration of anatomy, which can result in pain, discomfort, musculoskeletal disorder, and physical harm.

Hazard from abnormal situations implies loss of power, emergency condition and fault. Possible effects can be hazards associated with the need to evacuate passengers from remote locations (e.g. following ride breakdown). As a result, discomfort, panic and falling can occur.

Hazards of human activities that should be predicted are numerous. For example, neglected or not used personal protective equipment can result in exposure to hazardous agents such as shock, sunburn and abrasion. Public or passengers not respecting the alerts can lead to hazards from reasonably foreseeable users' behavior (such as anxiety, escape, etc.), and potential consequences can be falling, crushing, and impacts. A lot of patience should be dedicated to education and training of staff to prevent operator failures and wrong procedure maneuvers. Panic is one of the hazards that should be carefully considered and emergency procedures planned with the intention to prevent incidents. Sudden illness of either operator or passenger should be predicted and procedures planned. Finally, inappropriate guests' behavior should be predicted.

Hazards from lack of information can occur due to an incomplete manual and inadequate training. Appropriate signs, either with pictograms or written instructions and warnings, should be placed in visible places.

Environmental hazards should also be assessed. Snow, hail, rain, ice, lightning strike, fog, earthquake, and high winds can also be very dangerous and should be taken into consideration so actions can be taken to prevent bad consequences in these situations.

A great help for the Risk Assessment development is taking into consideration factors linked to the social environment. When addressing safety, the answers to these questions should be based on the following:

- Likelihood of being injured;
- Interaction with persons (parent, carers, operators);
- Human development and behavior;
- Lack of knowledge and experience;
- Social/environmental factors;

Additionally, the human factors might be affected by the:

- physical environment;
- climate;
- language;
- social environment;
- attitudes and beliefs;
- knowledge, information, communication and user's experience.

Special attention should be paid to materials selection and quality of construction elements. Steels used for structural components should be harmonized with SRPS EN 10025 (5). Aluminum alloys shall be selected in accordance with SRPS EN 1999-1-1 (6). Selection of timber, plastic composites, and concrete shall be in accordance with internationally accepted standards and guidelines (SRPS EN 1995-1-1 (7)) (SRPS EN 1992-1-1 (8)). Bolts, screws and studs shall be in accordance with SRPS EN ISO 898-1, and SRPS EN 14399 series (9,10).

In addition to the calculation of the load-bearing capacity of materials or accessories, which relates directly to the safety of passengers or the public, certificates, manufacturer's markings or testing will also be provided. When ropes, chains, safety devices, connectors and adapters are used, strict standards should be used (11-26). Short link chains for lifting purposes should be used in accordance with the standard EN 818 series (27).

Amusement devices shall be calculated in operative, inoperative, fully loaded, partially loaded and unbalanced conditions.

3. OPERATION, MAINTENANCE AND USE

This standard deals with installing, assembling, disassembling, operating, handling, maintaining, repairing, modifying and inspecting amusement devices and is addressed to controllers, operators, attendants and inspection bodies.

Standard documentation contains an operating manual that includes maintenance instructions, Non-Destructive Testing (NDT) schedule, operative instructions, amusement device log and official technical dossier. The standard contains the existence of the controller and his responsibilities. The controller or nominated delegate shall:

- ensure that the required documentation accompanies the amusement device when being bought, sold or otherwise transferred or supplied;
- select and train operators and attendants;
- assemble and disassemble safely;
- ensure safe operation in full compliance with laws, prescriptions and regulations issued by local and national authorities;
- service, maintain, repair and modify safely;
- where required, ensure that only amusement devices which have a valid operational permit and are examined and tested by appropriately independent inspection bodies are operated;
- ensure the emergency procedures are established, well documented and regularly practiced;
- provide full instructions on the control or communications system.

3.1. Selection and training of staff

Obtaining suitable and competent staff involves selection, training, testing of knowledge and understanding, monitoring, auditing and keeping records. The controller would select workers able to put the safety of the public first, to follow procedures conscientiously, and to have the maturity and authority to give confidence to the public.

Adequate training shall be provided to all employees and training records kept. Training shall be appropriate to the risks and given in a way that those being trained can understand.

The operator and attendants of amusement devices shall demonstrate competency in the operation of amusement devices according to the manual(s).

No operators or attendants of the amusement device shall be younger than required by national standards or law in the country of use.

Operators and attendants, depending on their duties, shall be provided with suitable and sufficient information and training in the working of their amusement devices, covering:

- systems of work for safe operation, including speed limits and any other specific safety measures;
- procedures for reporting breakdowns, defects or unusual occurrences;
- loading and unloading procedures;
- passenger restrictions such as height and weight limits, medical conditions, limited accessibility (guest behavior);
- control of waiting and viewing areas;
- use and operation of passenger containment and passenger restraint systems including the checking of restraint closure;
- controlled/emergency stop procedures;
- emergency procedures, including passenger evacuation.

4. REQUIREMENTS FOR INSPECTION DURING DESIGN, MANUFACTURE, OPERATION AND USE

The initial approval of the amusement device shall comprise a design review, inspection of the manufacturing process and initial inspection and testing.

4.1. Review of design documents

The design documents shall include: design risk assessment, design calculations, stress and fatigue analysis and stability verification. Also, documents on structural and mechanical parts, hydraulic and pneumatic parts, drive units, bearings and brakes, and safety devices should be available for review.

Documents that include installation, operation, maintenance and inspection information should also be a part of the documentation.

4.2. Inspection requirements

Inspection shall, as a minimum, verify the following:

- conformity of the main dimensions, clearance distances and dimensions, free (easy) running of moving parts;
- existence of all constructional components indicated in the construction documents;
- compliance with the major dimensions of the load-carrying constructional components and their connections. Inaccessible constructional components or component groups are only to be dismantled when there are doubts concerning the compliance of the dimensions or the correct assembly/mounting;

- compliance with the weight on which the calculations are based for such parts whose excess weight would cause the permissible stress on connections or constructional components to be exceeded, or whose shortage in weight might affect the safety of the equipment as far as lifting-off, sliding or tilting-over are concerned;
- conformity of the required certificates concerning material specification and quality, e.g. strength, durability, fire resistance;
- conformity of the electrical, electronic, hydraulic/pneumatic equipment with wiring, circuit diagrams, including when possible, software, observance of the relevant EN and/or IEC standards and the applicable regulations and standards;
- compliance with welding procedures specifications, shaping, machining, thermal treatment, coating of the structural and safety-related parts by NDT (Non-Destructive Testing).

The inspection of bearings, motors, enclosed drive units, switch and control units and similar components is required for, and limited to, only such cases where their failure could affect the safety of persons.

4.3. Initial inspection and testing

The initial inspection and testing shall consist of several separate inspections and tests which, taken together, demonstrate that at the time and place of the testing and inspection the amusement device is capable of performing in accordance with the approved design documents. Functional tests concerning the movements unloaded and under full load are required. During the trial run, the following functions and conditions shall be checked:

- safety envelope for passengers relative to any moving parts or other objects;
- correct working of sequential, forced and interlocked control systems;
- the specified speeds, accelerations and safety critical weights - counterweights;
- the working pressures of hydraulic/ pneumatic systems;
- the correct connection of electric supply;
- the setting of inclination control switches, terminal switches and other control switches as well as overload protections;
- the safety devices;
- the operation of the ride and the accelerations and decelerations under normal working conditions and in cases of emergency.

4.4. Pre-use inspection and review – Procedures proposal

Initial approvals, inspections and tests shall be carried out by applying the following procedures:

The inspection body shall be in accordance with EN ISO/IEC 17020 [28].

All safety-relevant design documents as well as the completed amusement device shall be subjected to review and inspection. After a successful inspection, a document confirming compliance with EN 13814-1:2019 and EN 13814-3:2019 can be issued.

The results of the various inspections and reviews shall become an integral part of the amusement device log.

The initial approval of amusement devices shall comprise a design review, inspection of the manufacturing process and initial inspection and testing.

4.5. In-service inspection (periodical test)

The purpose of in-service inspection is to check on the fitness of an amusement device for continued further use during its operational life. It is a check on the safety-related components of an amusement device to ensure that they have not deteriorated to such an extent that the ride cannot continue to operate safely. The findings of the inspection and the requirements shall be recorded in a report along with the interval to the next inspection.

4. CONCLUSION

The safety control system for amusement park equipment in Serbia appears to be insufficient, and this may have contributed to several serious incidents in recent years. Because the majority of amusement park visitors are children and adolescents, a comprehensive and systematic approach to ensuring their safety is essential.

Based on these findings, we propose that such an approach should include strict oversight of equipment manufacturers during the design and production phases to ensure compliance with applicable safety standards. Furthermore, all amusement park equipment should undergo thorough inspection and testing before being placed on the market or put into operation. Operators should be required to conduct daily inspections and routine safety checks of all equipment in use. Finally, a system of periodic inspections performed by independent qualified professionals should be established, with inspections carried out at least once a year.

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Professional paper

SAFETY MEASURES IN PRIMARY AND SECONDARY SCHOOLS

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Abstract: *School safety has become an increasingly important issue in modern educational systems due to the growing complexity of security risks affecting students, staff, and educational institutions. This paper provides an overview of the main forms of protection and security threats in primary and secondary schools, with a focus on physical and technical security measures. The paper examines both internal and external threats that may compromise the safety of the educational environment and discusses recent developments in the Croatian school safety framework. Particular attention is given to the measures introduced following the attack at Prečko Primary School, including the Protocol on Entry and Exit Control in Educational Institutions and the introduction of the Operational Officer for Security and Civil Protection. The findings highlight the importance of a comprehensive approach that combines preventive, organizational, and technical measures in order to enhance school safety and improve security risk management.*

Keywords: *school safety, security measures, risk managment, physical protection, violence prevention*

1. INTRODUCTION

Safety in educational institutions, particularly primary and secondary schools, has become a key issue in contemporary education systems. Safety measures encompass both the prevention of potential high-risk situations and the appropriate response to specific incidents, with the aim of protecting students and all employees involved in their education and care. Educational institutions are not only places of learning but also environments that play a crucial role in the development of students' social skills, emotional well-being, and personal growth. Recent events at Prečko Primary School in Zagreb have drawn the attention of the public and relevant authorities, including the Government, to the importance of preventive safety measures and the need to strengthen student protection within the education system. Given the various challenges and threats that may arise in schools, it is essential to implement adequate safety measures that ensure the security and well-being of all participants in the educational process.

2. GLOBAL OVERVIEW OF SCHOOL TRAGEDIES

Tragic events that have occurred in educational institutions worldwide, whether resulting from accidents or intentional attacks, have highlighted the importance of developing effective security policies and preventive measures in schools. Numerous international incidents have prompted the improvement of security protocols, surveillance systems, and emergency response procedures. In Croatia, the attack at Prečko Primary School in Zagreb in 2024 received significant public attention and further emphasized the need to strengthen the safety of students and staff, as well as to implement new protective measures within educational institutions. [1].

3. FORMS OF PROTECTION IN SCHOOLS

Security in educational institutions requires a comprehensive approach that encompasses various forms of protection. The integration of private, physical and technical protection forms the basis for creating a safe environment for students, teachers and other school employees.

3.1. Private protection

Private security activities include the protection of persons and property by applying physical and technical protection and by preparing threat assessments to assess security risks and determine appropriate protective measures. Its purpose is to prevent threats and protect people, facilities and property in accordance with the Private Security Act, [2].

3.2. Physical protection

Physical protection involves the direct protection of persons and property through the presence of authorized security personnel. It aims to prevent security threats, control access to protected areas, and provide a timely response to incidents and emergency situations in accordance with applicable legal regulations, [2].

3.3. Technical protection

Technical protection includes the application of systems and devices designed to safeguard people, property, and facilities from various security threats. It typically involves access control systems, video surveillance, anti-burglary and fire protection systems, as well as other technological measures that enable continuous monitoring, timely detection of threats, and more effective security risk management, [3].

4. FORMS OF SECURITY THREATS IN EDUCATIONAL INSTITUTIONS

Security threats in primary and secondary schools can be categorized as internal or external. Internal threats include peer violence, violence directed at school staff, and cyber threats within the school environment. External threats encompass unauthorized access to school premises, natural

disasters, public health emergencies such as pandemics, terrorist threats, bomb threats, and the presence of firearms or other dangerous objects that may endanger the safety of students and staff, [1].

5. SECURITY MEASURES IN EDUCATIONAL INSTITUTIONS

Violence prevention is a key element of creating a safe school environment. The Protocol on Procedures in Cases of Violence in Schools establishes preventive measures and response procedures aimed at protecting students and school staff from violence and other forms of abuse. It requires school employees to report suspected violations of students' rights and to cooperate with the school principal and the competent social welfare authorities. These measures contribute to the early identification of risks, timely intervention, and the prevention of violent incidents within the school environment, [4].

In addition to general preventive measures, recent events have led to the introduction of additional security measures aimed at improving safety in Croatian schools

Following the attack at Prečko Primary School in late 2024, additional security measures were introduced to further strengthen the protection of studente, staff, and school property. Among the most significant changes were the adoption of the Protocol on Entry and Exit Control in Educational Institutions and the introduction of the position of an Operational Officer for Security and Civil Protection.

The Protocol on Entry and Exit Control in Educational Institutions was established to improve school safety through enhanced access control. It regulates the entry of students, staff, and visitors, as well as procedures for emergency and crisis situations, with the aim of preventing unauthorized access and strengthening security within school premises, [5].

The Operational Officer for Security and Civil Protection is responsible for monitoring and assessing security risks, implementing security plans and protocols, coordinating responses to crisis situations, and cooperating with relevant emergency services. The role also includes organizing training activities and overseeing the implementation of security measures, thereby contributing to a more systematic approach to safety management in educational institutions, [6]

6. CONCLUSION

Safety in educational institutions is one of the key prerequisites for a high-quality teaching and learning environment. Various internal and external threats require a systematic approach that combines organizational, technical, and preventive security measures. Events that have affected educational systems in recent years, particularly the attack at Prečko Primary School, have highlighted the need to strengthen safety standards and improve risk management practices. The introduction of the Protocol on Entry and Exit Control in Educational Institutions and the position of the Operational Officer for Security and Civil Protection represents an important step toward enhancing school safety. However, the long-term effectiveness of these measures will depend on their consistent implementation, the cooperation of all stakeholders, and continuous investment in education, prevention, and the development of a strong safety culture. Only a comprehensive approach can ensure a safe and supportive environment for students and staff.

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Review article

CBRN THREATS TO CRITICAL INFRASTRUCTURE AS A MODERN SECURITY PROBLEM

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Abstract: *As one of the extremely dangerous and perhaps the most dangerous threats today, the abuse of chemical, biological, radiological and nuclear weapons stands out, especially if they are available to terrorists. Although the extent of the consequences of CBRN weapons depends on the weapon used, they have in common that they represent a real danger not only to the life and health of people, the environment, but also to the economy and business community causing mass casualties that can destroy health systems and cause public panic and social unrest, requiring special efforts to remediate. When we talk about risks in critical infrastructure, we should certainly take into account that critical infrastructure systems are interconnected and that endangering these systems with CBRN threats can lead to catastrophic consequences, especially if there is an interruption of work and function in densely populated areas.*

Keywords: *CBRN threats, critical infrastructure, risk, security*

1. INTRODUCTION

One of the most important security challenges of the new era is the issue of protecting critical infrastructure, because the functioning of modern society largely depends on the effective protection of significant infrastructure facilities. Critical infrastructures within a country represent complex systems. The great importance that such infrastructures have for society requires the creation of sufficiently good security measures that will serve to reduce the risk of disruption. Infrastructures such as the transport network, water, energy, chemical and nuclear industries, as well as information and telecommunications technologies provide the basic conditions for the functioning of individuals and groups. As such, the system, on which almost all everyday activities depend, simultaneously becomes the subject of attack and threat. [1]

Understanding the importance of critical infrastructure for national and international security is a prerequisite for finding adequate strategies for their protection. Adequate strategies for the protection of critical infrastructure achieve an acceptable level of loss and damage in the event of natural disasters, while the security system is more effective in preventing and overcoming such situations. Building an adequate critical infrastructure protection system today represents an extremely complex task for all states. [2]

Critical infrastructures are vulnerable to CBRN threats and are characterized by their interdependence, which leads to large-scale adverse events. This scenario requires the establishment of vital societal functions in the shortest possible time, so it is here that the system's ability to predict, respond to, and quickly recover from incidents is reflected. The resilience of critical infrastructure systems is then tested. [3]

Of all the types of, biological weapons actually represent the greatest unknown and cause the greatest fear, since they are developing and spreading at a frighteningly rapid rate, especially in the era of advances in science, genetic engineering and biotechnology. The potential destructiveness of biological weapons is such that they are considered a strategic threat because they can produce suffering on a wide scale. [4]

In this paper, the authors review the national legal and regulatory framework of the Republic of Serbia for CBRN threats to critical infrastructure.

The main method that will be used is the content analysis method. It will analyze legal and by-laws of the Republic of Serbia, strategic documents, reports of state institutions, scientific papers, professional literature and other relevant sources related to CBRN threats to critical infrastructure, natural disasters and risk management.

2. CBRN THREATS AND CRITICAL INFRASTRUCTURE FACILITIES

When talking about critical infrastructure, we can distinguish the following types: state, regional and global. State infrastructures can be divided into local, regional, national and international. Critical infrastructure can represent a facility where an emergency occurs, and as such requires protection, while on the other hand, it can also be a means of reducing the danger and mitigating the consequences of the situation [5]

Chemical, biological, radiological and nuclear incidents often threaten critical infrastructure systems and the world is in great fear of terrorism because these agents are dangerous substances suitable for terrorist activities. Critical infrastructure facilities are attractive targets for CBRN attacks and the consequences are devastating because it is well known that without the functioning of critical infrastructure it is impossible to imagine everyday life.

The most endangered sectors of critical infrastructure from CBRN threats are water and food supply systems, public transport facilities, energy and health sectors. These facilities are tempting targets because of the potential to cause mass casualties, long-term contamination, fear and panic in society. [6]

The role of critical infrastructure facilities in emergencies caused by CBRN incidents is particularly important:

- production and distribution of electricity (hydroelectric power plants, thermal power plants, transmission lines, substations),
- production and supply of energy (refineries, oil fields, gas storage facilities, oil derivatives, main oil and gas pipelines),
- telecommunications (transmission routes, fixed and mobile telephony, power plants), − production and supply of drinking water (water sources and factories, distribution centers),
- production and supply of food (food production plants), − health care (health institutions and facilities),
- material and cultural goods (museums, theaters, cultural and historical monuments) and
- national parks. [7]

Among the most exposed sectors of critical infrastructure to CBRN attacks (chemical, biological, radiological and nuclear) are those systems whose destruction or contamination cause massive human casualties, prolonged panic and economic collapse. They are:

The water supply and food sectors are extremely vulnerable to biological agents and liquid chemical poisons. Food production systems represent an extremely vulnerable point.

Minimal misuse of CBRN agents leads to mass poisoning, soil contamination.

The healthcare sector represents the first line of defense, which in the event of a direct CBRN attack becomes the primary target in order to prevent the care of the injured.

The attack on the energy sector causes a cascading effect, because without electricity and gas, the continuity of work of hospitals is interrupted, communication is interrupted... Nuclear power plants and chemical plants are particularly interesting targets of attack.

The traffic and transportation sector with a special emphasis on subways and underground stations because they are closed spaces with a high density of passengers, ideal for the spread of gaseous chemical and biological agents.

Also, airports are a frequent and interesting target of attacks, because a large number of people pass through, which allows the rapid spread of biological agents before symptoms even appear.

Given that CBRN threats have the most dangerous consequences for unprotected personnel, the main focus should be on appropriate information and training. [8]

3. NORMATIVE AND LEGAL PROTECTION AGAINST CBRN THREAT IN THE REPUBLIC OF SERBIA

Today, we can emphasize that, in order to preserve security and stability, the Republic of Serbia is taking all necessary measures and activities arising from international initiatives and ratified agreements. Engagement on the international stage for each state also implies certain obligations towards the organizations in whose work it participates. In the case of Serbia, the most significant international obligations arise from the official strategic goal of the state to become a member state of the European Union. Serbia officially became a candidate country for EU membership in 2012, and opened the first negotiation chapters in December 2015. The process of accession to the

Union involves harmonizing the state's legislative framework with the existing common normative framework and principles of the EU. By signing the Stabilization and Association Agreement with the European Union, the Republic of Serbia committed to harmonizing its legislation with that of the European Union. As in other areas, state authorities are obliged to improve legal regulations relating to the trade, use and misuse of hazardous materials. [5]

The umbrella document that recognizes the proliferation of weapons of mass destruction and HBRN accidents as a threat to the country's security is the National Security Strategy of the Republic of Serbia. This document classifies various contemporary challenges, risks and threats in detail. [9]

The legal framework governing the defense, prevention and response to CBRN threats in the Republic of Serbia relies on a set of specialized laws that are aligned with international conventions.

It should be emphasized the importance of the Law on Radiation and Nuclear Safety and Security, Official Gazette of the RS 2019, which applies to all activities that include the peaceful use of nuclear energy and ionizing radiation in the territory or under the authority or control of the Republic of Serbia. This law applies to all situations of planned, existing and extraordinary exposure to ionizing radiation that include the risk of exposure to ionizing radiation, which cannot be ignored from the point of view of protection from ionizing radiation of the individual, the population and the environment. [10]

The Law on Disaster Risk Reduction and Emergency Management ("Official Gazette of RS", No. 87/2018), regulates disaster risk reduction, prevention and strengthening of resilience and readiness of individuals and communities to respond to the consequences of disasters, protection and rescue of people, material, cultural and other assets, rights and obligations of citizens, associations, legal entities, bodies of local self-government units, autonomous provinces and the Republic of Serbia, management of emergency situations, functioning of civil protection, early warning, notification and alerting, international cooperation, inspection supervision and other matters of importance for the organization and functioning of the disaster risk reduction and emergency management system. [11]

The Law on Chemicals ("Official Gazette of the RS", No. 36/2009, 88/2010, 92/2011, 93/2012 and 25/2015) regulates the integrated management of chemicals, classification, packaging and labeling of chemicals, the integral register of chemicals and the register of chemicals placed on the market, restrictions and prohibitions on the production, placing on the market and use of chemicals, import and export of certain dangerous chemicals, licenses for carrying out trade activities and licenses for the use of particularly dangerous chemicals, systematic monitoring of chemicals, availability of data, supervision and other issues of importance for the management of chemicals. [12]

A very important legal document is the Law on Fire Protection, which regulates the fire protection system, the rights and obligations of state authorities, autonomous province authorities and local self-government units, companies, other legal and natural persons, fire service organizations, supervision of the implementation of this law and other issues of importance for the fire protection system.

The provisions of this law are accordingly applied to protection against explosions. [13]

Traffic in sources of ionizing radiation, radioactive and nuclear materials is procurement, sale, import, export, transit and any other way of putting such materials into circulation. The activity of trading sources of ionizing radiation, radioactive and nuclear materials can be carried out by a legal entity, that is, an entrepreneur who has a license to carry out the activity of trading sources

of ionizing radiation, radioactive and nuclear materials. The circulation of one or more sources of ionizing radiation, radioactive and nuclear materials can only be carried out with a previously obtained permit from the Directorate for Radiation and Nuclear Safety and Security of Serbia.

Control of unauthorized and illegal traffic of radioactive and nuclear materials across the border of the Republic of Serbia is carried out at border crossings. The direct control of the unauthorized and illegal traffic of radioactive and nuclear materials is carried out by members of the Customs Administration using portable radiation indicators and stationary radiation monitors. Customs officials are tasked with detecting any dose exceeding the natural level of radiation for a given location during the control of goods and passengers.

The resistance of critical infrastructure in Serbia against CBRN (chemical, biological, radiological and nuclear) threats is regulated by the Law on Critical Infrastructure [14] and the Regulation on Criteria for Identification of Critical Infrastructure. The Critical Infrastructure Act regulates the identification, designation and protection of systems and networks whose disruption would have serious consequences for national security, human health and the economy. [15]

Interesting results were obtained by examining the perception of institutional capacities, levels of preparedness and coordination between several organizations in the Republic of Serbia responsible for responding to chemical, biological, radiological and nuclear incidents. The research conducted by the group of authors [16] indicates a generally developed awareness of CBRN risks and the importance of effective early response. The results highlight the importance of targeted capacity-building measures, including regular interagency training, improved access to resources for detection and protection, and better distribution of standardized operating procedures.

4. CONCLUSION

CBRN threats are increasingly global in nature. The scope of the risk is constantly growing, and so is the number of potentially endangered people and material resources, as well as the disruption of the ecological balance. Since CBRN incidents involve risks with devastating consequences, cumulative and accidental, anthropogenic and natural, they represent a special type of risk. Risk management is an organized process of identifying and measuring risks, selecting, developing and implementing risk management options, and monitoring risks.

Due to their consequences, CBRN accidents are remembered for a long time and require a quick response of all forces of the social community in their prevention, protection and rescue of people, material and cultural assets, as well as elimination of the resulting consequences.

The modern security environment is characterized by the increasingly pronounced occurrence of CBRN threats, which pose a serious challenge, especially for critical infrastructure. These incidents can occur as a result of criminal and terrorist activities, industrial and technological accidents, but also natural epidemiological phenomena, which is why their consequences often exceed the capacity of individual institutions. In practice, the question often arises as to whether the institutional, normative and operational capacities of the Republic of Serbia enable a timely and adequate response to CBRN threats. Most critical infrastructure facilities have their own security systems that include video surveillance, alarm systems and access control. These security systems have the function of preventing and detecting all threats, so they can indirectly detect CBRN threats. For example,

access control can prevent unauthorized entry of carriers of CBRN agents. However, not only do not all critical facilities have this system, but some characteristics of CBRN agents make it impossible to identify the threat using classic means of protection.

The strengthening of international cooperation and the implementation of EU standards are key drivers of the modernization of the CBRN system in Serbia. As a candidate country and a border state with the EU, Serbia should implement it - the CER directive because it also shares strategic critical infrastructure with the EU. The goal of the directive is to strengthen the resilience of critical entities in the energy, transport, health, digital infrastructure, water supply, food industry, and finance sectors.

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Professional paper

SUSTAINABILITY-INFORMED DECISION-MAKING: A CASE-STUDY OF KAUFLAND

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Abstract: *Although sustainability reporting is often perceived as a regulatory requirement, truly informed decision-making considers the long- and short-term impacts of business activities on both the environment and society, with consequences ultimately affecting the end user. Business decisions integrate not only economic performance but also sustainability data, including environmental indicators (resource use, emissions, waste, etc.) and social indicators (safety, diversity, community engagement, etc.). This paper investigates the sustainability data provided in Kaufland's sustainability report to support informed decision-making, using content analysis to examine environmental and social indicators. The findings highlight that sustainability indicators can contribute to informed decision-making when they are transformed from reporting metrics into actionable management information.*

Keywords: *sustainability reporting, sustainability report analysis, decision-making*

1. INTRODUCTION

Business decision-making has traditionally relied on financial information, with organizational performance primarily assessed through economic outcomes such as profitability, efficiency, and shareholder value. However, increasing environmental challenges, social expectations, regulatory developments, and stakeholder pressures have expanded the information required for effective decision-making. Contemporary organizations increasingly need to consider not only financial outcomes but also the environmental and social consequences of their activities [1, 2].

Sustainability information provides organizations with measurable data concerning environmental and social impacts, including resource consumption, emissions, waste generation, employee conditions, occupational health and safety, diversity, and community relationships. Such information enables organizations to identify sustainability-related risks, evaluate performance, and consider the broader consequences of business activities [3].

Sustainability reporting tends to become an established mechanism for communicating organizational sustainability performance. Frameworks such as Global Reporting Initiative (GRI) have contributed to the standardization of sustainability disclosures by defining indicators through which organizations report environmental, social, and governance impacts [4]. However, sustainability reporting should not automatically be interpreted as evidence that sustainability information directly influences managerial decisions. Reporting primarily serves accountability and transparency purposes, whereas decision usefulness depends on whether sustainability information is incorporated into organizational processes and management systems [5, 6].

The distinction between sustainability reporting and sustainability information is therefore important. Sustainability reporting represents the communication of sustainability performance, while sustainability information represents the underlying data may support strategic, tactical, and operational decisions. When integrated into management systems, sustainability information can complement financial information by providing insights into risks, opportunities, resource efficiency, and organizational impacts [7, 8].

2. SUSTAINABILITY INFORMATION AS A DECISION-SUPPORT TOOL

Organizations make decisions at different managerial levels, each requiring different types of information. Following Anthony's [9] distinction between strategic planning, management control, and operational control, managerial decisions can be categorized into strategic, tactical and operational levels. Each level requires sustainability information with different characteristics and purposes.

Strategic managers require aggregated and forward-looking information that supports long-term decisions related to organizational direction, investments, risks, and opportunities. Tactical managers require information that supports the implementation of sustainability objectives through programs, resource allocation, and performance monitoring. Operational managers require detailed and timely information related to daily activities and processes. Sustainability information required at each of the management levels are proposed in Table 1. The usefulness of sustainability information depends on its relevance, reliability, and integration into organizational decision processes. Sustainability indicators become valuable when they are connected with organizational objectives, responsibilities, and performance evaluation systems rather than being collected solely for reporting purposes [3, 7].

Table 1: Management levels and sustainability information requirements

Decision level	Information purpose	Examples of sustainability information
Strategic	Support long-term planning, risk assessment, and value creation	Climate risks, emission trends, resource dependency, sustainability opportunities
Tactical	Support implementation, resource allocation, and monitoring	Sustainability programs, supplier performance, improvement initiatives
Operational	Support process control and corrective actions	Energy use, waste generation, material consumption, safety indicators

Source: Adapted from [7, 8, 9]

Strategic decisions influence the long-term direction and resilience of organizations. Sustainability information may support strategic decision-making by improving understanding of environment constraints, social expectations, and emerging risks. Environmental indicators such as greenhouse gas emissions, energy consumption, and resource use may inform decisions regarding decarbonization strategies, investment priorities, and operational transformation. Social indicators related to workforce development, diversity, health and safety, and stakeholder relationships may support decisions concerning human capital, organizational reputation, and responsible business practices. The development of integrated thinking has emphasized that organizations create value through interactions between financial, environmental, and social factors [1, 10]. However, research indicates that the strategic use of sustainability information remains uneven. In many organizations, sustainability information continues to serve primarily external accountability purposes rather than being fully integrated into strategic decision processes [3]. Therefore, sustainability information should be viewed as a potential strategic resource rather than an automatic driver of strategic decisions. Its influence depends on organizational capabilities, management commitment, and the extent to which sustainability considerations are embedded within strategic planning processes [11].

Tactical decision-making involves translating strategic objectives into specific programs, investments, and operational initiatives. At this level, sustainability information assists managers in implementing sustainability strategies and evaluating progress. Environmental information can support tactical decisions concerning energy efficiency, waste reduction, sustainable procurement, and resource optimization. For example, data on material consumption and emissions can assist managers in developing improvement programs and evaluating their effectiveness. Social information can support tactical decisions related to employee development, workplace safety, diversity initiatives, and supplier responsibility. Indicators related to training, occupational incidents, and workforce composition provide information that can guide targeted management activities. The effectiveness of sustainability information at the tactical level depends on whether indicators are linked to organizational targets and management control systems. Research suggests that sustainability information is more likely to influence managerial activities when incorporated into planning, monitoring, and performance evaluation processes [12, 7].

Operational decisions concern daily processes, resource use, and continuous improvement activities. At this level, sustainability information is typical more detailed and directly connected to organizational activities. Environmental indicators such as energy consumption, water use, emissions, and waste generation allow managers to identify inefficiencies and implement corrective actions. Social indicators such as workplace injuries, training participation, and employee-related measures support operational decisions concerning safety, workforce management, and compliance. Environmental management accounting research demonstrates that operational sustainability information can improve visibility of resource flows and support efficiency improvements [3]. However, operational usefulness depends on the existence of reliable measurement systems and processes that enable managers to translate sustainability data into practical actions. Thus, sustainability information at the operational level is most valuable when embedded within routine management activities rather than treated only as a reporting requirement.

3. SUSTAINABILITY INDICATORS AND DECISION USEFULNESS

Sustainability indicators provide measurable information about organizational environmental and social impacts. Although sustainability indicators are commonly used within reporting frameworks to improve transparency and accountability, they may also support internal decision-making when integrated into management processes. The GRI Standards provide a structured approach for identifying and reporting sustainability impacts through standardized indicators [4].

The decision usefulness of sustainability indicators depends on their relevance to specific managerial needs. Strategic managers require information that supports long-term risk assessment and organizational positioning, tactical managers require information for program implementation and performance monitoring, while operational managers require detailed information for process control and improvement. Therefore, sustainability indicators provide decision support when they are connected with organizational objectives and management activities.

3.1. Environmental indicators and decision-making

Environmental indicators represent one of the most developed categories of sustainability information because environmental impacts can often be quantified and directly linked to organizational activities. Indicators related to materials, energy, water, biodiversity, emissions, and waste provide information regarding resource dependency, environmental risks, efficiency opportunities, and regulatory compliance.

Material indicators support decisions concerning resource efficiency, sustainable procurement, and circular economy strategies. Energy and emissions indicators are particularly relevant for climate-related decisions-making, including decarbonization strategies and efficiency improvements. Water, biodiversity, and waste indicators provide information useful for environmental risk management and operational improvement.

The environmental indicators analyzed in Kaufland's sustainability reporting can therefore be interpreted as information supporting different management decisions, ranging from strategic sustainability planning to operational monitoring, as shown in table 2

Table 2: Environmental indicators and decision usefulness

GRI Standards	Indicator	Strategic decisions	Tactical desisions	Operational decisions
GRI 301	Materials	Circular economy strategy; sustainable procurement; transition toward sustainable materials	Supplier selection; packaging optimization; material-efficiency programs	Material consumption tracking
GRI 302	Energy	Energy transition strategy; renewable energy investments; decarbonization	Energy efficiency programs; technology investments	Energy monitoring and consumption control
GRI 303	Waters	Water stewardship strategy; assessment of water-related risks	Water efficiency initiatives and improvement programs	Water consumption monitoring; wastewater control

GRI Standards	Indicator	Strategic decisions	Tactical desisions	Operational decisions
GRI 304	Biodiversity	Biodiversity protection strategy; responsible site selection	Environmental compliance systems; supplier requirements	Monitoring of environmental compliance
GRI 305	Emissions	Climate strategy; emissions reduction investments; climate risk management	Emission reduction programs; supplier emission initiatives	Emissions monitoring and corrective actions
GRI 306	Waste	Circular economy transition; long-term waste strategy	Waste reduction programs; recycling initiatives	Waste separation and tracking

Source: Adapted from [4, 3,]

3.1. Social indicators and decision-making

Social indicators provide information regarding organizational relationships with employees, suppliers, customers, and communities. Compared with environmental indicators, social indicators often involve more complex qualitative dimensions; however, they provide important information concerning human capital, organizational culture, stakeholder relationship, and social risks [2].

Environmental indicators provide information about workforce structure, employment practices, and employee turnover. Such information may support strategic decisions related to human resource development and organizational capability. Health and safety indicators support decisions concerning workplace risk management and employee well-being.

Training and diversity indicators provide information regarding workforce development and organizational culture. At the strategic level, they may support decisions related to long-term competence development and inclusion strategies, while at operational level they assist with monitoring participation and implementation (table 3).

Indicators related to suppliers, communities, product safety, and marketing practices extend sustainability considerations beyond organizational boundaries. These indicators can support responsible sourcing strategies, stakeholder engagement, customer trust, and compliance activities.

Table 3: Social indicators and decision usefulness

GRI Standards	Indicator	Strategic decisions	Tactical desisions	Operational decisions
GRI 401	Employment	Human resource strategy; employer branding	Recruitment and retention programs	Hiring and workforce administration
GRI 402	Labor/Management relations	Labor relations strategy; employee engagement and social dialogue governance	Consultation procedures; workforce communication and change management programs	Employee consultation processes; notification and communication practices
GRI 403	Health & Safety	Safety governance strategy	Safety training and prevention programs	Incident monitoring and workplace control

GRI Standards	Indicator	Strategic decisions	Tactical desisions	Operational decisions
GRI 404	Training	Workforce capability development strategy	Training systems and development programs	Training implementation monitoring
GRI 405	Diversity	Diversity and inclusion strategy	Equality initiatives and inclusion programs	Workforce composition monitoring
GRI 406	Non-discrimination	Ethical governance and human rights commitments	Complaint management systems	Case handling and corrective actions
GRI 413	Communities	Stakeholder relationship strategy, CSR strategy	Community programs and partnerships	Implementation of community activities
GRI 414	Suppliers	Responsible sourcing strategy	Supplier assessment and audits	Supplier compliance monitoring
GRI 416	Product safety	Product safety governance	Quality assurance systems	Product testing and recall procedures
GRI 417	Marketing	Transparency and customer trust strategy	Communication compliance system	Product information control

Source: Adapted from [4, 2, 6]

4. MANAGERIAL IMPLICATIONS

The analysis demonstrates that sustainability information can support different types of managerial decisions depending on organizational needs and decision levels. However, sustainability indicators do not automatically generate managerial value. Their usefulness depends on whether organizations integrate sustainability information into planning, control, and performance management systems.

At the strategic level, sustainability information can assist managers in identifying long-term environmental and social risks, evaluating opportunities, and developing sustainability-oriented strategies. Environmental indicators such as emissions and resource use can inform climate-related decisions, while social indicators can support workforce and stakeholder strategies.

At the tactical level, sustainability information assists managers in implementing sustainability objectives through specific programs and resource allocation decisions. Indicators provide a basis for monitoring progress, evaluating initiatives, and improving sustainability performance.

At the operational level, sustainability indicators support daily management activities by providing measurable information about processes, resources consumption, compliance, and improvement opportunities. The managerial implications are summarized in Table 4.

Table 4: Sustainability information and managerial decision levels

Decision level	Main purpose of sustainability information	Examples of sustainability activities
Strategic	Identify long-term risks, opportunities, and sustainability-related value creation	Sustainability strategy, climate planning, investment decisions, stakeholder strategy
Tactical	Implement sustainability objectives and monitor performance	Sustainability programs, supplier initiatives, improvement projects
Operational	Control processes and improve daily performance	Resource monitoring, waste reduction, safety management, corrective actions

Source: Adapted from [7, 8, 9]

5. CONCLUSION

Sustainability-informed decision-making requires organizations to consider information beyond traditional financial performance measures. Environmental and social indicators provide measurable information that can help organizations understand the impacts, risks, and opportunities associated with their activities.

This paper examined sustainability information as a potential decision-support resource by analyzing environmental and social indicators reported through Kaufland's sustainability reporting. The analysis demonstrates that indicators related to materials, energy, emissions, waste, employment, health and safety, diversity, suppliers, and communities can provide information relevant to strategic, tactical, and operational management decisions.

However, sustainability reporting itself should not be interpreted as automatically producing managerial decision-making benefits. The value of sustainability information depends on how organizations integrate indicators into management processes, establish accountability, and connect sustainability objectives with operational activities. The findings highlight that sustainability indicators can contribute to informed decision-making when they are transformed from reporting metrics into actionable management information.

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Professional paper

CONSUMER PERCEPTION OF PERSONALIZED DESSERTS PRODUCED BY 3D PRINTING TECHNOLOGY

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Abstract: *This study examines consumer perceptions of personalized desserts produced using 3D-printing technology. The findings indicate that additive manufacturing in food production remains at an early stage of consumer adoption, with attitudes shaped by curiosity, technological apprehension, and interest in the possibilities of customization. Personalized nutritional profiles and complex geometries are particularly attractive to younger and more technologically oriented consumers; however, broader acceptance depends on sensory quality, perceived safety, and the perceived naturalness of the product. Consumers show strong interest in visually intricate desserts that are difficult to produce using conventional methods, creating an initial 'wow effect'. At the same time, food neophobia and the perception of 3D-printed products as artificial or highly processed remain important barriers. Secondary data were analysed using general methods of analysis and deduction, while primary survey data were processed using descriptive statistical methods.*

Keywords: *consumer acceptance, personalized desserts, sensory evaluation, 3D food printing, food neophobia*

1. INTRODUCTION

The contemporary food industry is positioned at the intersection of traditional production methods and the digital transformation enabled by additive manufacturing, commonly referred to as 3D food printing. Although 3D printing is already established in many industries as a prototyping and manufacturing tool, its application in gastronomy, particularly in the production of personalized desserts, raises important questions concerning design, nutritional customization, and sustainability [1, 2]. Its principal advantage lies in the ability to create complex geometric structures and individualized nutritional profiles that cannot readily be achieved through conventional pastry-making techniques [2, 3]. Nevertheless, the market success of 3D-printed desserts depends not only on technical precision but also on the psychological and sensory factors that shape consumer attitudes. While the visual 'wow effect' may attract younger consumers, perceptions of artificiality and unfamiliar processing methods can impede wider acceptance [2]. The market therefore remains in an early-adoption phase, characterized by both enthusiasm for innovation and apprehension toward unfamiliar food technologies. This study investigates consumer attitudes toward personalized 3D-printed desserts and identifies the principal factors that facilitate or inhibit their acceptance, with particular emphasis on visual appeal, perceived safety, taste expectations, and product naturalness.

2. PERSONALIZED DESSERTS PRODUCED BY 3D PRINTING TECHNOLOGY

Within contemporary pastry arts, where the boundaries between craftsmanship and technology are increasingly blurred, 3D food printing (3DFP) has emerged as an innovative production method. Originally developed for industrial applications, the technology offers a new approach to personalized confectionery by combining digital precision with gastronomic design. Its principal advantage is the capacity to create geometries that are difficult or impossible to produce manually. Edible materials such as chocolate, fruit purées, sugar pastes, and creams are deposited layer by layer, most commonly by extrusion, to create complex lattice structures, fractals, and customized inscriptions [3]. In this context, the dessert becomes not only a food product but also a digitally designed object tailored to individual preferences. The technology also enables precise control over ingredients, allowing products to be formulated with a specified energy value, without selected allergens, or with added vitamins and proteins. Such functionality is particularly relevant to personalized and functional nutrition. Despite these advantages, consumer acceptance remains a decisive factor. Technological scepticism may arise from the perception that machine-produced food is artificial or inferior to products prepared by skilled pastry chefs [3]. This barrier may be reduced through co-creation: when consumers participate in designing a dessert through a digital application, they may develop a stronger emotional connection with the product and perceive it as a distinctive, premium experience rather than as an anonymous industrial product.

3. TECHNICAL REQUIREMENTS FOR PERSONALIZED DESSERTS PRODUCED BY 3D-PRINTING TECHNOLOGY

The successful implementation of 3D printing in pastry making requires the synchronization of hardware, software, and the specific chemical properties of food materials. Unlike standard 3D printing of plastics or metals, food printing faces unique challenges such as raw material variability and strict hygiene standards.

The most commonly used system is syringe-based extrusion, which often utilizes compressed air:

- Dosing precision: The system must ensure a constant flow of material without air bubbles to achieve standardized layers.
- Temperature control: For materials like chocolate or specific creams, the printer must feature a built-in heating and cooling system (thermoregulation). If chocolate is not kept at an exact temperature, it will lose its gloss and structural stability.
- Nozzle diameter: Standard food-printing nozzles generally range from 0.8 to 1.5 mm. Smaller diameters enable finer detail and improved aesthetics but increase the risk of clogging [1, 3].

For a dessert to be successfully printed, the material must meet three critical technical parameters:

Viscosity: The material must be fluid enough to pass through the nozzle, yet viscous enough not to spread out after extrusion.

Solidification capability: Immediately upon exiting the nozzle, the layer must become firm enough to support the weight of subsequent layers.

Layer adhesion: Each new layer must bond physically or chemically with the preceding layer to prevent delamination [1, 3].

The personalization process begins in a digital environment:

- CAD modeling: Creating 3D models in software such as Fusion 360 or dedicated co-creation applications.
- Slicing: The software converts the 3D model into G-code, which instructs the printer regarding movement speed, material flow, and toolpath. For personalized confectionery products, printing speed must be optimized to balance product quality and production time [3].

From a technical standpoint, the printer must be designed according to "Food Grade" standards:

- Component materials: All parts coming into contact with food (cylinder, tubes, nozzles) must be made of stainless steel or certified corrosion-resistant polymers.
- Hygienic design: The device must be easy to disassemble to permit thorough cleaning and sanitization and to prevent microbial growth in inaccessible areas of the extrusion system.
- Post-processing requirements: Production requirements may extend beyond the printing stage. Many printed desserts require rapid cooling, baking, dehydration, or another finishing process to achieve the desired final texture. Consequently, the printer may need to be integrated with supporting laboratory or kitchen equipment [3, 4].

4. EXPERIMENTAL STUDY

4.1. CONSUMER PERCEPTION OF PERSONALIZED DESSERTS PRODUCED BY 3D-PRINTING TECHNOLOGY

Consumer perception is a key determinant of the wider adoption and commercialization of 3D-printed food. Although 3D food printing is increasingly presented as an innovative approach to producing nutritionally tailored, visually appealing, and functional food products, consumer acceptance remains uncertain. Consumers often respond cautiously to unfamiliar food technologies, particularly when products depart from traditional methods of preparation and consumption [6, 7]. This caution is commonly associated with limited knowledge of the technology, perceptions of unnaturalness, concerns about food safety, and uncertainty regarding taste, nutritional value, and health effects [6].

Previous studies indicate that 3D food printing can enhance perceptions of innovation and product quality, but these positive impressions do not necessarily result in higher sensory acceptance. Compared with conventionally produced foods, 3D-printed products are often evaluated more favourably in terms of appearance and selected sensory attributes [5, 6]. However, perceived technological sophistication does not necessarily translate into greater overall acceptance, particularly when taste and texture remain the dominant criteria in food evaluation [8].

Visual appearance and design complexity have a particularly important role in shaping initial consumer impressions. Because 3D printing enables complex shapes, precise structures, and personalized geometries that are difficult to achieve using conventional methods, consumers may perceive such products as more attractive and engaging [5]. Greater visual complexity can improve evaluations of appearance, although it may not exert the same effect on overall acceptability, taste, or texture [8]. Thus, visual appeal can stimulate interest and positive expectations, but final acceptance depends on the complete sensory experience.

Consumer awareness is another important factor. Clear information about the operation of 3D food printers, ingredient composition, process safety, and potential benefits may contribute to more favourable attitudes [6]. Nevertheless, information alone does not always produce a significant increase in sensory acceptance or perceived quality. More positive attitudes are likely when consumers can directly experience the product, for example through tasting. Studies have shown that some participants expressed greater willingness to consume 3D-printed food again after direct exposure, underlining the importance of experiential familiarization [6, 8].

Despite its potential advantages, 3D-printed food faces several barriers to consumer acceptance. The most frequently reported concerns relate to edibility, healthfulness, nutritional value, and safety [6, 7]. Some consumers perceive printed food as artificial, unnatural, or excessively processed, which can reduce willingness to consume it [6]. Even the term 'printer' may evoke associations with plastics, inks, and industrial materials rather than food. The perceived naturalness of the ingredients is therefore important: products are more likely to be evaluated positively when they are clearly described as being made from familiar, natural, and nutritionally valuable ingredients. Conversely, unclear information about composition, processing, or raw-material origin may increase perceived risk and reduce acceptance [5, 6].

The intention to purchase and consume 3D-printed food is influenced by psychological, social, and sensory factors. Research based on the theory of planned behaviour identifies consumer attitudes,

subjective norms, perceived behavioural control, sensory appeal, food neophobia, technology neophobia, perceived health risks, and environmental acceptability as relevant predictors [6, 7]. Consumers who are more open to innovation and who perceive 3D-printed food as useful, safe, and environmentally acceptable generally report greater willingness to purchase and consume it. In contrast, food neophobia, technological apprehension, and health concerns can substantially reduce interest [7].

In the case of personalized 3D-printed desserts, consumer perception is especially complex because the product combines technological innovation, functional nutrition, personalization, and the hedonic characteristics associated with desserts. Consumers may respond positively to the possibility of customizing shape, portion size, texture, and nutritional composition, particularly when the capacity of 3D printing to address individual dietary needs is emphasized [5]. However, because desserts are primarily associated with pleasure and sensory appeal, acceptance will depend on whether consumers perceive the products as not only innovative and functional but also tasty, safe, natural, and visually attractive [6, 8].

Research on consumer perceptions of personalized 3D-printed desserts is therefore important for assessing the market potential of the technology. It enables the identification of factors that encourage or restrict adoption, including awareness, trust in the technology, sensory expectations, attitudes toward functional foods, the importance of natural ingredients, and perceptions of sustainability [6, 7]. The findings may support the development of products that are aligned not only with technological capabilities but also with consumer expectations, needs, and values [5].

Survey research is particularly useful for examining consumer motivations and perceived barriers related to 3D-printed desserts. Responses are expected to vary according to prior technological experience, openness to innovation, and attitudes toward unfamiliar foods.

4.2. RESEARCH INSTRUMENT

A structured questionnaire was developed for the primary study to examine consumer perceptions of personalized desserts produced using 3D-printing technology. The questionnaire comprised five thematic sections: demographic characteristics; attitudes toward the technology and visual aesthetics of 3D-printed food; perceptions of personalization; sensory expectations and trust; and a final open-ended question.

Respondents were recruited through voluntary participation and completed a structured questionnaire during 2025. The questionnaire was administered both online and in person. Participation was anonymous and voluntary, and respondents were informed about the purpose of the study before completing the questionnaire.

The questionnaire was developed specifically for this exploratory study based on themes identified in previous research on consumer perceptions and acceptance of 3D-printed food [5–8]. As the study was exploratory in nature, no pilot study was conducted prior to the main data collection.

4.3. STATISTICAL ANALYSIS

The study was conducted on a sample of 50 respondents, and the collected data were analysed using descriptive statistical methods. For closed-ended questions, absolute frequencies and relative proportions were calculated to describe the distribution of responses. For statements measured on a Likert scale, the arithmetic mean, median, and mode were calculated. The arithmetic mean was

used to indicate the average level of agreement with each statement, the median to identify the central response, and the mode to determine the most frequently selected rating. The results are presented in tables to facilitate interpretation.

Because the sample comprised 50 respondents, the findings should be interpreted as indicative evidence of consumer perceptions of personalized 3D-printed desserts and should not be generalized to the broader population.

4.4. RESULTS

The sample included respondents from several age groups. Participants aged 18-25 years formed the largest group (15 respondents; 30%), followed by those aged 26-40 years (26%), those aged 41-55 years (20%), and respondents older than 55 years (24%). The age distribution was therefore relatively balanced, without a pronounced dominance of any single category. Respondents younger than 40 accounted for 56% of the sample, while those older than 40 accounted for 44%. This distribution provides insight into the attitudes of different age groups toward 3D-printed food and personalized desserts, which is relevant because perceptions of emerging food technologies may vary according to age, previous experience, and openness to innovation.The sample consisted of 28 men (56%) and 22 women (44%); no respondent selected the category 'other'. Although men were slightly more represented, the gender distribution can be considered reasonably balanced and provides an adequate basis for interpreting differences in attitudes across respondents.

Table 1. Awareness and previous experience of respondents

Question	Response	Number of respondents	Share
Had respondents previously heard of 3D food-printing technology?	Yes	39	78 %
	No	11	22 %
Had respondents tried food produced using a 3D printer?	Yes	0	0 %
	No	50	100 %

Most respondents (78%) had previously heard of 3D food-printing technology, indicating a relatively high level of general awareness. However, none had consumed food produced using a 3D printer. Their attitudes therefore appear to be based primarily on expectations and perceptions rather than direct experience.

Table 2. Distribution of responses and summary statistics for Likert-scale statements

Statement	1	2	3	4	5	Mean	Median	Mode
3D printing enables more visually attractive desserts	0	0	2	6	42	4,80	5	5
Food produced by a 3D printer appears artificial and unnatural	9	8	12	10	11	3,12	3	3
I am concerned about the safety of food produced by a 3D printer	0	0	0	0	50	5,00	5	5
3D printing is the future because it enables precise control of ingredients	0	33	10	7	0	2,48	2	2

The strongest positive response concerned the visual appeal of 3D-printed desserts, with a mean rating of 4.80 and 84% of respondents selecting the maximum score of 5. This finding is consistent with previous research indicating that 3D food printing can enhance perceptions of innovation and product appearance [5, 6]. At the same time, respondents expressed considerable uncertainty regarding the nature and safety of printed food. Opinions regarding the artificial or

unnatural character of 3D-printed food were divided, with 42% of respondents agreeing or strongly agreeing with this perception, 34% disagreeing, and 24% remaining neutral. This pattern is in line with previous findings suggesting that limited familiarity with the technology and perceptions of unnaturalness may contribute to consumer caution [6].

Food safety represented the strongest concern in the present study, with all respondents assigning the maximum score of 5. This result further reflects concerns identified in previous research regarding the safety of unfamiliar food-production technologies [6]. This finding should not be interpreted as evidence that consumers objectively consider 3D-printed food unsafe, but rather as an indication of very high perceived safety concern in this particular sample. In contrast, the statement that 3D printing represents the future because it enables precise control of ingredients received the lowest mean score (2.48), suggesting that the perceived technological advantages of 3D printing do not necessarily translate into confidence in the technology or broader consumer acceptance.

Table 3. Purchase motives and willingness to pay a premium

Category	Response	Number of respondents	Share
Purchase motive	Independent design of the dessert shape	24	48 %
	Nutritional customization	6	12 %
	Trying a new technology	11	22 %
	Unique gift	9	18 %
Willingness to pay a premium	The price should remain the same	44	88 %
	Up to 10% higher	6	12 %
	Up to 30% higher	0	0 %
	Twice the price	0	0 %

The most important purchase motive was the possibility of independently designing the shape of the dessert, selected by 48% of respondents. Interest in trying a new technology ranked second (22%), whereas nutritional customization was the least frequently selected motive. These findings suggest that consumers may be particularly attracted to the creative and personalized aspects of 3D food printing rather than to its potential nutritional benefits. This finding highlights the potential importance of consumer familiarity and confidence in the technology, as greater understanding of the printing process, ingredients, safety aspects, and possible benefits may help reduce uncertainty surrounding 3D-printed foods [6].Providing such information may therefore be particularly important for increasing consumer confidence and translating interest in personalization and new technology into actual purchase intention.

Despite the interest in personalization observed in the present study, 88% of respondents were unwilling to pay a higher price, while only 12% would accept a price increase of up to 10%. This suggests that although personalization may increase the attractiveness of 3D-printed desserts, consumers may not yet perceive it as sufficient added value to justify a higher price.

Table 4. Confidence in taste and preferred tasting location

Category	Response	Number of respondents	Share
Belief that the taste would be equally good	Yes	13	26 %
	No	37	74 %
	Unsure	0	0 %

Category	Response	Number of respondents	Share
Preferred tasting location	Luxury restaurant	28	56 %
	Local pastry shop	0	0 %
	Public event or food festival	7	14 %
	I would not like to try it	15	30 %

Consistent with previous research showing that technological novelty does not necessarily translate into greater food acceptance when sensory qualities remain important [8], the present findings indicate that the novelty of the technology was not sufficient to overcome consumers' expectations regarding sensory quality. Most respondents (74%) did not believe that a 3D-printed dessert could taste as good as one prepared manually by a pastry chef. Since none of the respondents had previously tasted a 3D-printed dessert, these evaluations reflected anticipated rather than experienced taste. This may indicate that concerns about the expected sensory properties of 3D-printed food remain an important barrier to its acceptance. Nevertheless, 56% of respondents expressed a willingness to try a 3D-printed dessert in a luxury restaurant, suggesting that an attractive and trusted consumption setting may encourage consumers to overcome their initial reservations. In contrast, 30% indicated that they would not wish to try such a dessert in any of the proposed settings.

The results show that respondents recognize the aesthetic and personalization potential of 3D food printing, particularly its capacity to create visually attractive and individually designed desserts. At the same time, substantial distrust remains regarding food safety and taste. Although most respondents were aware of the technology, none had direct experience with 3D-printed food; consequently, their attitudes largely reflect expectations about an unfamiliar technology. The greatest market potential appears to lie in personalized design and presentation in a professional, controlled environment. However, limited willingness to pay a premium suggests that market introduction would require competitive pricing, transparent evidence of safety, and opportunities for consumers to taste the products before purchase.

Several limitations should be considered when interpreting the findings. First, the study was conducted on a relatively small sample of 50 respondents. The sample size limits the statistical precision of the findings and prevents reliable generalization to the broader consumer population. Second, the use of a non-probability sampling procedure may have introduced selection bias, as individuals who voluntarily participated may differ from consumers who were not reached or did not choose to participate. Third, none of the respondents had previously consumed food produced using a 3D printer. Consequently, the reported attitudes primarily reflect expectations and perceptions of an unfamiliar technology rather than direct sensory experience. This is particularly relevant for the findings concerning taste, texture, and safety. Fourth, the analysis was limited to descriptive statistics and therefore does not establish statistically significant differences between demographic groups or causal relationships between consumer characteristics and acceptance. Future research should therefore employ larger and more diverse probability-based samples where feasible, include direct tasting of 3D-printed desserts, and apply inferential statistical methods to examine differences in consumer perceptions across demographic and experiential groups.

5. CONCLUSION

3D-printed desserts offer considerable potential for reducing material waste, enabling precise portioning, and expanding creative possibilities in food design. Nevertheless, the present findings indicate that technological potential alone is insufficient to ensure consumer acceptance. Respondents recognized the visual and personalization advantages of 3D food printing, but they also expressed strong concerns regarding safety and taste. As none of the participants had previously consumed 3D-printed food, their evaluations were based on expectations rather than direct sensory experience. The most promising opportunities appear to involve personalized design and product presentation in professional, controlled settings. However, successful commercialization will require competitive pricing, clear communication about ingredients and safety, and opportunities for product tasting. Given the small sample size, the findings should be regarded as exploratory and should be validated in future studies involving larger and more diverse samples and direct sensory evaluation.

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Professional paper

STRESS MANAGEMENT AS AN INTEGRAL PART OF OCCUPATIONAL SAFETY AND HEALTH IN THE NONPROFIT SECTOR

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Abstract: *Psychosocial risks are an increasingly important aspect of modern occupational health and safety systems, with workplace stress recognized as a major cause of reduced work ability and burnout. The nonprofit sector faces specific challenges, including limited financial resources, strong emotional engagement with beneficiaries, and employees performing multiple roles, all of which may increase exposure to stress. This paper examines theoretical and empirical knowledge on stress management within occupational health and safety systems and explores possibilities for integrating burnout prevention measures into the policies of nonprofit organizations. Particular attention is given to models of psychosocial risk management, including primary, secondary, and tertiary prevention approaches. The literature highlights the need for a systematic and proactive approach that includes psychosocial risk assessment, employee and management education, organizational support, and clear prevention procedures. Stress management should therefore be understood not only as an individual responsibility but also as an essential component of organizational strategy and occupational health protection in the nonprofit sector.*

Keywords: *stress management, safety at work, non-profit sector, burnout*

1. INTRODUCTION

Prolonged exposure to stress can lead to a decline in motivation, efficiency, and the quality of interpersonal relationships; therefore, it is crucial to recognize and understand stress and burnoutphenomena that occur across all fields of work, particularly in sectors where employees face emotionally demanding tasks and limited resources. Non-profit organizations stand out in this regard, as their employees shoulder significant social responsibility alongside their professional challenges. These organizations play a pivotal role in supporting vulnerable and marginalized groups while contending with specific challenges, such as limited financial resources, intense emotional engagement with service users, and the need for staff to juggle multiple roles simultaneously,

resulting in constant exposure to stressful situations. Given that workplace stress poses a serious problem for both employees and organizations, it is of utmost importance to foster healthy work environments, eliminate sources of workplace stress, and reduce workers' exposure to stressors.

2. STRESS IN THE NONPROFIT SECTOR

2.1. Non-profit organizations

The distinctive nature of non-profit organizations stems from their mission to create positive social change, making them an essential factor in the development and preservation of the community's quality of life. A non-profit organization is one whose primary goal is to provide services to society on a non-profit basis [1-3].

Non-profit organizations serve the public interest, yet their primary purpose is not profit generation; they emerge, operate, and are defined by their environment. This environment typically encompasses political, economic, social, and technological (PEST) components. Depending on the situation, each of these components plays a greater or lesser role in society and its functioning, thereby driving the activities of civil society institutions [4].

Non-profit organizations can be classified according to various criteria, with the most common being their field of activity, funding method, or legal form. In the Republic of Croatia, under current legislative frameworks, organizations operating on a non-profit basis can be categorized into two main groups:

1) Budget users – state (government) non-profit organizations

2) Non-profit organizations (in the strict sense) – non-state (non-governmental) non-profit organizations [5].

Table 2. Types of non-profit organizations

GROUP	ORIGINAL TITLE
NFP	Not For Profit Organization
NFGO	Not For Gain Organization
PVO	Private Voluntery Organization
NGO	Non Govermental Organization
GONGO	Govermental Organized Non Govermental Organizations
QUANGO	Quasi Autonomous Non-Govermental Organizations
BONGO	Business Organized Non-Govermental Organizations
FOMGO	Funder Organized Non Govermental Organizations
PONGO	Political Non-Govermental Organizations

This division clearly shows how non-profit organizations can be distinguished according to several criteria. First, the difference between governmental and non-governmental forms is emphasized. Secondly, the volunteer character stands out, which is one of the fundamental indicators of the non-profit sector. Thirdly, the character of the founder is also taken into account, i.e. the fact that organizations can arise from the initiative of the government, the business sector, foundations or political actors [6].

In the Republic of Croatia, the fundamental legal forms of non-profit organizations are associations, foundations, and institutions. Each of these forms has specific characteristics, a legal framework, and a scope of activity, yet they share the common trait of not operating for profit, but rather to meet specific social needs. Associations represent the most widespread form of non-profit organization in Croatia and constitute the core of civil society. They are established through the voluntary association of at least three natural or legal persons for the purpose of pursuing and promoting shared interests, beliefs, and goals [7]. Foundations are established based on specific assets used permanently to achieve goals of general or public benefit. Their operations are not based on membership, but rather on the management of assets dedicated to a specific purpose [8]. Institutions are established to carry out activities of public interest on a permanent basis, most commonly in the fields of education, science, culture, healthcare, and social welfare. Unlike associations and foundations, institutions conduct their activities in a more systematic and organized manner, and their work is often linked to the provision of public services. Examples of institutions include schools, universities, museums, homes for the elderly and infirm, and healthcare facilities [9].

According to the Act on Financial Operations and Accounting of Non-Profit Organizations, non-profit organizations are "all legal entities whose primary objective in establishment and operation is not the generation of profit, but rather the fulfillment of specific social needs, and which use their revenues exclusively to achieve the objectives for which they were established"[10].

2.2. Workplace stress

Work-related stress is currently one of the leading problems facing the workforce and ranks among the most common reasons for leaving a job.

According to research by the European Agency for Safety and Health at Work (EU-OSHA):

- 50% to 60% of lost working days can be attributed to psychosocial risks and work-related stress
- around 50% of European workers consider work-related stress to be common in their workplace
- nearly 80% of employers in Europe are concerned about work-related stress, while 40% believe that psychosocial risks are more difficult to manage than other occupational health and safety risks
- only a small proportion of organizations at the European level have procedures in place to manage workplace stress, harassment, and violence, citing the sensitivity of the topic and a lack of expertise as the main reasons [11].

Work-related stress refers to health-related and psychological changes resulting from the cumulative impact of workplace stressors over an extended period, manifesting as physiological, emotional, and cognitive reactions, as well as changes in the worker's behavior [12].

Most causes of stress or stressors stem from the nature and content of the work, the characteristics of the work organization, and the organization's social climate [13]. Such factors result in negative psychological, physical, and social consequences for employees, as well as adverse outcomes for the organization itself.

The effects of stress can be viewed in terms of the impact on the worker (physical, emotional, cognitive, and behavioral symptoms) and the impact on the organization [14].

When a significant number of employees are under stress, the consequences extend to the organization itself. Such an organization becomes "unhealthy" because it fails to realize the full potential of its employees. This not only reduces overall efficiency but also jeopardizes the organization's long-term viability.

The problems stress causes for an organization can be both short-term and long-term.

Short-term problems – increased rates of workplace injuries and accidents (due to reduced employee concentration), more frequent absenteeism and lost workdays due to stress-related illnesses, prolonged sick leave, higher employee turnover, reduced organizational loyalty and a greater willingness to change employers, as well as potential employee lawsuits regarding stress-induced illnesses.

Long-term problems – if the aforementioned difficulties are not resolved, the organization achieves poorer business results and faces increased costs, declining profitability, and reduced market competitiveness, thereby jeopardizing its long-term survival.

The effects of stress, both at the individual and organizational levels, clearly demonstrate the seriousness and complexity of this issue. Given that prolonged exposure to stress can compromise employee health and destabilize the organization, it is essential to develop effective strategies and methods to mitigate it.

Table 1: Workplace stress management

Worker	Manager	Organization	Society
Better health and well-being	Working with healthy, motivated, and productive workers	Increased efficiency, reduced number of accidents and injuries, reduced sick leave costs	Reduced healthcare and pension system costs

Effective management of psychosocial risks and work-related stress yields significant benefits at all levels from the individual worker to the organization as a whole, and consequently, at the level of the national economy [11].

Stress-coping techniques encompass various strategies an individual uses to avoid, mitigate, or overcome stressful situations. These techniques may be directed toward problem-solving or emotional relief, with the choice depending on the specific situation and the individual's characteristics; thus, we distinguish between problem-focused coping, emotion-focused coping, avoidance coping, and coping through seeking social support [15].

The choice of coping technique depends on the type of stressful event, personality traits, prior experience, knowledge, the duration of exposure to stress, the perception of threat, and available material resources. Individuals who employ strategies tailored to the specific situation are more successful in protecting themselves against the negative consequences of stress; they are more optimistic, possess greater self-confidence, and are more open to new life experiences.

2.3. Burnout

Prolonged exposure to stress leads to so-called "burnout". Burnout results from the interaction of specific organizational conditions, personal characteristics, and individual aspirations [16]. Employee burnout in the non-profit sector most often stems from the specific challenges and limitations these organizations face. The main causes can be classified into several categories: [17]

a) Work overload and unrealistic expectations

In non-profit organizations, the principle of "more work with fewer resources" often prevails. Employees are expected to take on different roles, so in addition to operational tasks, they often deal with administration, project management or direct work with users. This leads to chronic fatigue and the feeling that the demands always exceed the available capacities.

b) Limited financial and personnel resources

Many organizations depend on time-limited projects and donations, which makes planning and stability difficult. In addition, the lack of professional staff often means that key functions rely on a small number of employees and sometimes volunteers.

c) Emotional Exhaustion and Empathy Fatigue

Working with vulnerable groups requires a high level of emotional engagement. Prolonged exposure to the problems and suffering of others can lead to so-called "empathy fatigue," a state in which employees gradually lose the ability to connect emotionally and experience internal exhaustion.

d) Lack of support from management and colleagues

When organizational culture does not foster open communication and mutual support, employees are more likely to feel isolated and left to fend for themselves. A lack of quality leadership further increases stress levels and uncertainty.

e) Impaired work-life balance

More than half of non-profit organization leaders state that they find it difficult to separate their personal and professional lives. Prolonged overtime work and availability outside of working hours often lead to feelings of exhaustion and reduced job satisfaction.

f) Organizational changes and uncertainty

Frequent changes in funding, projects, or the direction of work introduce additional instability. Employees face uncertainty regarding job security, which increases anxiety and contributes to the risk of burnout.

3. RESEARCH METHODOLOGY AND RESULTS

A study on employee burnout was conducted in the Karlovac area during August 2025. A total of 18 employees from five diverse non-profit organizations operating within the local community participated in the study (Frendofon Association, Carpe Diem Association, DrONe Association, Karlovac Association of Spinal Cord Injured Persons, and the "Korak" Women's Group Karlovac). The survey was carried out using a structured questionnaire covering causes of stress, the frequency of burnout, perceptions of organizational support, and stress-coping strategies. The study provided answers to the following research questions**:**

1. What are the most common sources of stress among respondents?
2. How do respondents perceive signs of burnout at work?
3. What are the most commonly used coping strategies?

The participating organizations operate across a wide range of fields from providing support to persons with disabilities and children with developmental difficulties, to promoting youth cultural and creative expression, and advocating for human rights and gender equality. This diversity allows for a broader perspective on the specific challenges faced by association employees and offers the opportunity to compare burnout risks and manifestations across different segments of the non-profit sector. The study's limitations primarily relate to sample size and geographic specificity, meaning the results cannot be generalized to all non-profit organizations in Croatia. Nevertheless, the research provides valuable insight into the situation at the local level and can serve as a foundation for future, more extensive analyses. It would be particularly beneficial to conduct longitudinal studies that track the progression of burnout symptoms over an extended period and examine the effectiveness of various prevention measures.

3.1. Research results

The key findings addressing the research questions are presented below.

Causes of stress

To gain a deeper understanding of the mechanisms behind stress, respondents were asked to identify its primary sources. The responses reveal a wide range of factors: staff shortages and excessive workloads, tight deadlines and overlapping tasks, financial insecurity and reliance on project funding, demanding work with clients (individuals in crisis situations, as well as women and children who are victims of violence), and difficulties in collaborating with institutions. Some respondents also highlighted interpersonal relationships within the workplace, while a smaller number of employees reported experiencing no stress at all. This diversity of responses underscores the complexity of factors contributing to work-related stress, clearly highlighting a combination of organizational and emotional pressures.

Experiencing signs of burnout

When asked whether they had ever experienced signs of burnout—such as emotional exhaustion, a drop in motivation, or cynicism—77.8% of employees answered affirmatively. A smaller proportion of respondents (16.7%) stated they had not encountered such experiences, while 5.6% were unsure. These results clearly indicate that burnout is a prevalent issue among association employees, further underscoring the importance of preventive measures and the strengthening of support systems.

Stress Coping Strategies

When asked about the strategies they employ, respondents cited a variety of approaches, indicating individual differences in coping methods. The most frequently mentioned strategy was taking breaks and resting (72.2%), followed by talking to colleagues or supervisors (66.7%). Some employees engage in physical activity (38.9%), seek psychological support or psychotherapy (27.8%), or use relaxation techniques such as breathing exercises and meditation (27.8%). The combination of responses indicates that employees of non-profit organizations develop their own ways of dealing with pressure, although these methods are primarily aimed at the short-term alleviation of the effects of stress.

Potential benefits of systematic support

To examine employees' attitudes toward additional forms of assistance, a question was asked regarding whether they would utilize systematic organizational support for stress management (e.g., workshops, counseling, supervision). The results indicate that more than half of the respondents (55.6%) would certainly use such support, while an additional 27.8% would likely participate. Only a small proportion of employees (11.1%) felt they would not need such support.

In an open-ended question asking them to elaborate on their response, respondents emphasized that systematic support could offer multifaceted value—ranging from psychological well-being and burnout prevention to the exchange of experiences and advice, and the strengthening of team cohesion. Particular importance was placed on supervision as a safe space to discuss challenges without fear of repercussions. Some respondents indicated that they already utilize certain forms of professional assistance, while a smaller number felt they did not need such support, having developed their own self-help strategies.

The results indicate that employees of associations in Karlovac, despite strong motivation and commitment, operate daily under conditions of heavy workloads, financial instability, and emotionally demanding situations. Although the majority of respondents recognize and utilize certain forms of support, a significant proportion report signs of burnout. This confirms the need for a more systematic approach to prevention and the development of organizational measures that would improve employee well-being in the long term and ensure the more stable functioning of non-profit organizations.

4. CONCLUSION

Based on the research conducted and the literature review, the following key recommendations are made:

At the organizational level it is necessary to develop systematic support mechanisms for employees, including supervision, psychological counseling, and educational workshops on stress-coping techniques. Research results showed that some respondents had the opportunity to participate in supervision during their work and highlighted that this form of support was highly beneficial. Consequently, it is important to ensure that supervision becomes a regular and accessible form of support for all employees, given that study participants expressed a willingness to utilize this type of assistance again. It is also important to ensure a better distribution of work tasks and more flexible working hours, as well as to improve internal communication and team cohesion.

At the individual level, employees should be encouraged to develop personal stress management strategies, such as effective time management, setting boundaries, practicing healthy lifestyle habits, and strengthening social support. Developing emotional intelligence is particularly valuable, as it aids in recognizing and regulating one's own emotions.

At the societal level: since non-profit organizations operate in the public interest, it is essential to ensure greater institutional and financial support to create conditions for a more stable and healthy working environment—something that serves the interests of both employees and the wider community.

To conclude, these findings indicate that effective stress management should become an integral element of occupational safety and health systems in non-profit organizations. Investing in psychosocial risk prevention contributes not only to employee well-being but also to the long-term sustainability and quality of services provided by the non-profit sector.

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EMPLOYEE PERCEPTIONS OF SAFETY CULTURE

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Abstract: *Safety culture is an important determinant of safety performance in organizations. The elements that characterize a strong safety culture are especially relevant for practitioners aiming to ensure the safety and well-being of employees. The aim of this study is to investigate employees' perceptions of different safety culture elements and overall safety culture, and to assess their level of satisfaction with the safety culture in their organizations. Data were collected through an online questionnaire completed by 114 respondents. The results indicate a moderate perception of safety management practices, while a considerable number of respondents reported a lack of information about various safety-related activities within their organizations. The findings suggest that organizations should make greater efforts to inform and engage employees in developing a positive safety culture.*

Keywords: *safety culture, safety management, occupational safety, employee perception*

1. INTRODUCTION

Safety culture represents a complex system of shared ideas, beliefs, and values within an organization regarding workplace risks, accidents, and health protection [1]. It emphasizes the importance of both individual and group perceptions and behaviors, serving as a critical determinant of an organization's overall safety performance. A strong safety culture involves a continuous prioritization of safety at all levels of the organization, where employees at every rank are committed to personal responsibility for risk mitigation and active communication regarding safety concerns [2].

Safety culture is frequently used interchangeably with safety climate; however, the two concepts are distinct. Safety climate refers to the observable manifestations of safety culture and is shaped by employees' perceptions and attitudes at a given point in time [3]. Despite ongoing theoretical ambiguity and conceptual inconsistency, safety culture is widely regarded as a practical framework for enhancing workplace safety.

Many safety culture maturity models have been proposed to support improvements in safety culture and performance [4]. Based on Westrum's typology of organizational cultures (pathological, bureaucratic and generative [5]) Hudson [6] expanded the model from three to five stages, enabling a more nuanced and accurate classification while improving its accessibility for industry employees by incorporating terminology commonly used in practice [7]. The model proposed by Hudson (2001) provides a framework that classifies safety culture along a continuum. This model identifies five distinct levels: pathological, reactive, calculative, proactive, and generative. A *pathological safety culture* is characterized by a greater concern with avoiding blame or sanctions than with ensuring safety. In a *reactive safety culture,* safety improvements are primarily implemented in response to accidents or incidents that have already occurred. A *calculative safety culture* is characterized by the presence of formal risk management systems; however, safety procedures are often followed mechanically and may not be fully integrated into organizational values and practices. A *proactive safety culture* is characterized by established risk management systems and a growing recognition among both employees and management of the importance of safety. In a *generative safety culture*, safety is deeply embedded in organizational practices and values and is regarded as a fundamental aspect of everyday operations. Understanding these levels is essential for organizations striving to mature from mechanical compliance to a truly proactive safety framework [8].

The aim of this study was to examine employees' perceptions of the safety measures and practices that contribute to the development of organizational safety culture and to assess how they evaluate the level of safety culture in their organizations based on Hudson's safety culture maturity model.

2. METHODOLOGY AND RESULTS

Data were collected through an online questionnaire administered using a snowball sampling technique. The survey was distributed via social media and communication platforms, including Facebook, Facebook Messenger, Viber, and WhatsApp. Participation in the study was voluntary and anonymous. A total of 114 respondents completed the survey, and all valid responses were included in the analysis (Table 1).

Table 1: Sample description

Variable	Category	N=114	Percentage (%)
Gender	Male	37	32.46
	Female	77	67.54
Education	Elementary school	7	6.14
	Secondary school	72	63.16
	Bachelor's degree	17	14.91
	Professional specialist	17	14.91
	Master's degree	1	0.88
Jobs with special working conditions	Yes	54	47.37
	No	60	52.63

Variable	Category	N=114	Percentage (%)
Working experience	< 1 year	6	5.26
	1 – 5 years	42	36.84
	6 – 10 years	11	9.65
	11 – 15 years	15	13.16
	16 – 20 years	21	18.42
	> 20 years	19	16.67
Sectors	Primary and industrial sectors (agriculture, forestry and fishing; manufacturing industry)	34	29.82
	Infrastructure, construction and transport	19	16.67
	Trade, hospitality and other service activities	28	24.56
	Business and financial services	13	11.40
	Public and social services	20	17.54
Organization size	Small	26	22.81
	Medium	60	52.63
	Large	28	24.56

The average age of respondents was 33 years with an average of 11.5 years of work experience. The respondents were predominantly female and had completed secondary school education. Fewer than 48% of respondents reported working in jobs with special working conditions. Nearly half of the respondents (46.49%) worked in sectors characterized by high occupational risks, including primary and industrial activities, infrastructure, construction, and transportation. Most respondents (52.63%) worked in medium-sized organizations.

The statements used for the safety culture assessment were derived from the reviewed literature (Table 2). Specifically, statements 8 and 9 were based on the work of Konrad (2006) [9], while statements 10 through 13 were adapted from Kirwan, Reader, and Parand (2018) [10]. The statements were assessed using a five-point Likert scale, where 1 indicated strong disagreement and 5 indicated strong agreement. To accommodate respondents who were unable to evaluate a statement due to a lack of knowledge or experience, an additional response option, “I don't know,” was included. Cronbach's alpha for the 14-item safety culture scale was 0.93, indicating excellent internal consistency.

Table 2: Descriptive analysis: Safety culture assessment

Variable (statements)	I don't know	M	SD	Mode
The employer regularly visits the workplace and discusses safety matters with the workforce.	21	3.17	1.53	5
The organization provides regular and clear information on safety issues.	13	3.23	1.46	5
I can raise safety concerns at my workplace, knowing that the organization will take it seriously and inform me what they are doing about it.	11	3.34	1.52	5
In the organization where I work, safety is always a priority.	11	3.25	1.56	5
I can always get protective equipment and training when needed.	10	3.23	1.54	5
Everyone in the organization is involved in decision making related to safety.	15	2.98	1.51	5
Employees are asked for their opinion on safety.	15	2.84	1.58	1
When moving to a similar job, I do not need to repeat instructions on occupational safety.	15	3.24	1.56	5
Occupational safety is sufficiently integrated into the production process.	13	3.06	1.43	5

Variable (statements)	I don't know	M	SD	Mode
There are people in the organization who I do not want to work with because of their negative attitudes to safety. (R*)	30	3.42	1.45	5
My participation in safety-related activities (e.g., safety meetings) is sufficient.	23	2.84	1.40	3
As an employee, I am sufficiently involved in the safety risk assessment.	15	3.04	1.56	5
Incidents or events that could affect safety are properly investigated.	19	3.06	1.46	5
I am satisfied with the level of safety culture present in the organization.	15	3.19	1.43	5

* The statement is reverse coded.

The results indicate a moderate assessment of safety culture elements. Mean scores ranged from 2.84 to 3.42, suggesting generally moderate perceptions of safety-related practices within organizations. The lowest mean score (M = 2.84) was recorded for two statements: “Employees are asked for their opinion on safety” and “My participation in safety-related activities (e.g., safety meetings) is sufficient.” Moreover, the mode for the statement “Employees are asked for their opinion on safety” was 1, confirming that respondents evaluated this aspect of safety culture poorly. Similarly, respondents evaluated the statement “Employees are asked for their opinion on safety.” (2.98). These findings suggest a relatively low level of employee involvement in the development and implementation of the organizational safety framework. This is a matter of concern, as employee consultation is a key component of effective safety management. Workers are often most familiar with the hazards and risks associated with their tasks and can therefore provide valuable insights for identifying, assessing, and mitigating workplace risks. These findings indicate a relatively low level of employee consultation, which is significant because workers, being closest to the operational processes, possess essential practical knowledge for identifying and mitigating workplace hazards. This gap in communication suggests that management may not be fully leveraging the insights of those most exposed to risks. The significance of this finding is further underscored by the fact that 77.19% of respondents work in medium-sized and large organizations, where formalized health and safety management systems are generally expected to be implemented.

The moderate level of satisfaction with safety culture (3.19) within respondents’ organizations emphasizes the need for a more collaborative approach. Increasing employee involvement in risk assessments and safety-related decision-making is a critical step toward progressing from a calculative to a more proactive safety culture.

A notable proportion of respondents (ranging from 10 to 30) selected the “I don't know” response option for all statements, Specifically, 30 respondents were unable to assess the statement regarding colleagues’ negative attitudes toward safety, which may indicate limited awareness of their coworkers’ views on safety issues. Similarly, 23 respondents reported insufficient knowledge to evaluate whether their participation in safety-related activities was adequate, while 21 respondents were unable to assess whether employers regularly visited workplaces and discussed safety issues with employees. These findings suggest that a considerable number of employees are not sufficiently informed about certain safety-related activities and practices within their organizations. One possible explanation is that 52.63% of respondents reported not working in jobs with special working conditions, which may reduce their exposure to specific safety procedures, activities, and communication practices addressed by these statements.

The highest average score (3.42) was given to the statement “There are people in the organization who I do not want to work with because of their negative attitudes to safety.” As this item was reverse

coded, the result indicates that respondents generally disagreed with the statement, suggesting that negative attitudes toward safety are not perceived as widespread within their organizations. Even though 39.47% of the respondents disagreed or strongly disagreed with the statement, 26.32% cannot evaluate.

Respondents were subsequently asked to evaluate the level of safety culture that, in their opinion, predominated within their organizations (Table 3). The assessment was based on statements adapted from the safety culture framework developed by Patrick Hudson (2001) [6].

Table 3: Distribution of respondents by perceived safety culture type

Variable (statements)	N	Percentage (%)
The organization cares less about safety than about not being caught.	15	13.16
The organization seeks solutions to accidents and incidents after they have occurred.	17	14.91
The organization has systems in place to manage risks, but the system is applied mechanically. Staff and management follow procedures, but do not necessarily believe that these procedures are critical to their jobs or operations.	22	19.30
The organization has risk management systems in place, and staff and management have begun to believe that safety is truly important.	22	19.30
Safety behaviour is fully integrated into everything the organization does. The value system associated with safety and safe work is fully adopted as a belief, almost to the point of invisibility.	38	33.33
Total	114	100

The results indicate that the smallest number of respondents (13.16%) perceived their organization as exhibiting a pathological safety culture. A further 17 respondents (14.91%) identified their organization as having a reactive safety culture. An equal proportion of respondents (19.30%) perceived their organization as having a calculative and proactive safety culture. The largest group of respondents, 38 individuals (33.33%), identified their organization as having a generative safety culture.

A discrepancy can be observed between these findings and the average scores presented in Table 2. While respondents generally reported moderate levels of satisfaction with the safety culture in their organizations, the largest proportion classified their organizations as having a generative safety culture, which represents the highest level of safety culture maturity. One possible explanation for this inconsistency may be the occupational characteristics of the sample. Specifically, 52.63% of respondents reported that they do not work in jobs with special working conditions. It may therefore be assumed that employees in such work environments perceive safety risks as less prominent, which could contribute to more favorable assessments of their organization's safety culture. This often fosters a distorted sense of safety, leading employees to perceive the environment as safer than it actually is, until an incident occurs.

3. CONCLUSION

The empirical results highlight significant gaps in the practical implementation of safety culture. It is particularly concerning that the lowest mean score (M = 2.84) was observed for the statements related to employees being consulted on safety matters and their participation in safety-related activities, suggesting limited employee involvement in safety-related communication and decision-making processes.

This finding is of particular importance, as employee involvement is widely recognized as a key component of an effective safety culture. Employees possess first-hand knowledge of workplace hazards and operational risks associated with their daily tasks, making their input essential for identifying safety issues and developing appropriate preventive measures. This consultation must be carried out in a timely manner and must encompass critical activities, including the development of risk assessments, the planning of safety training, and the selection of appropriate personal protective equipment. Additionally, the notable number of “I don’t know” responses suggests that employees are not sufficiently informed about key safety-related activities within their organizations. Consequently, greater efforts should be made to encourage employee participation and consultation in safety-related matters, particularly given that respondents reported only a moderate level of satisfaction with the safety culture in their organizations (M = 3.19). Furthermore, it is imperative to emphasize the explicit legal obligation of organizations to ensure the active inclusion of workers, thereby fulfilling mandatory statutory provisions regarding information and consultation. Under national regulations, the employer is legally required to conduct timely consultations with workers on all health and safety matters, which encompasses critical preventive activities such as the development of risk assessments, the planning of safety training, and the selection of appropriate personal protective equipment [11].

The study revealed a notable paradox: while the evaluations of specific safety elements were moderate, the largest group of respondents (33.33%) perceived their organization as having the highest level of maturity – a generative safety culture. This discrepancy can likely be explained by the fact that 52.63% of respondents do not work in jobs with special working conditions. Such work environments may foster a subjective, yet unfounded, sense of high safety, as employees perceive risks as less salient until an incident occurs. Consequently, organizations must work on raising awareness of actual risks even in seemingly safe environments.

From a practical perspective, this study identifies specific elements for strengthening safety culture. The findings suggest that improvements in safety culture can be achieved through the active commitment and engagement of both supervisors and employees.

The findings of this study should be interpreted considering certain limitations. A number of respondents were unable to evaluate the statements describing safety culture, presumably because more than half of the respondents do not work in positions involving special working conditions. However, a considerable proportion of respondents reported working in high-risk industries (46.49%) and medium and large organizations (77.19%) which raises additional concerns regarding the moderate level of satisfaction with the safety culture and accentuates the lack of employee involvement. Furthermore, the classification of respondents' answers into specific safety culture types may have yielded different results if a larger number of measurement items had been included, thereby enabling a more comprehensive assessment of safety culture types. This would enhance the reliability and validity of the findings.

In addition to addressing the limitations outlined above, future research should also explore the predictive role of safety culture with respect to safety performance outcomes, an area that remains insufficiently examined in the extant literature. In light of the accelerating digital transformation of work environments, future research should investigate the role of artificial intelligence in fostering more proactive safety cultures, for example, AI-enabled hazard detection systems, predictive risk alerting mechanisms, and AI-augmented training and simulation frameworks.

This study adopted a descriptive approach aimed at examining employees' general perceptions of safety culture. Future research could build on these findings by exploring differences in safety

culture perceptions across demographic and occupational characteristics, such as gender, age, and job position. Another promising direction would be to investigate the extent to which these perceptions influence actual safety behaviours and related safety outcomes.

Safety culture represents one of the most important preventive mechanisms within organizations [12]. Consequently, organizations should invest not only in tangible and formal safety measures, such as regulations, instructions, procedures and personal protective equipment, but also in fostering the underlying values, beliefs, and behavioral norms that employees internalize and incorporate into their daily work practices [11]. The development of a strong safety culture encourages the consistent adoption of safe behaviors and contributes to the long-term effectiveness of occupational health and safety management.

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Professional paper

HISTORY OF SMOKING AND REGULATION IN THE HOSPITALITY SECTOR OF THE REPUBLIC OF CROATIA

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Abstract: *This professional review examines the historical development of smoking regulation in Croatian hospitality from an occupational safety and health (OSH) perspective. A narrative review and legal-historical analysis were conducted using primary Croatian legislation, WHO/WHO FCTC and EU documents, and selected peer-reviewed or institutional historical literature. The analysis shows a transition from general workplace protection of non-smokers under the 1996 Occupational Safety Act to detailed smoke-free rules with technically regulated hospitality exceptions. Because hospitality workers may experience repeated and prolonged second-hand-smoke exposure, formal legal compliance does not necessarily eliminate occupational exposure. WHO FCTC guidance further indicates that ventilation, filtration and designated smoking areas are not equivalent to a 100% smoke-free environment. Employer duties, worker protection and enforcement should therefore remain central to evaluation of Croatian regulation.*

Keywords: *smoking, second-hand smoke, hospitality workers, occupational safety and health, Croatia*

1. INTRODUCTION

Smoking has influenced social interaction in cafés, bars, restaurants and other hospitality settings for generations. In Croatia, as elsewhere in Europe, the transition from socially accepted indoor smoking to increasingly restrictive regulation has been gradual and at times contested. From an occupational safety and health perspective, however, the central issue is not the smoker's individual choice but the involuntary exposure of workers who may spend many hours in an environment in which tobacco smoke or emissions from related products are present [1, 2].

Second-hand tobacco smoke is an established health hazard. The World Health Organization (WHO) states that there is no safe level of exposure to second-hand tobacco smoke and that tobacco causes more than seven million deaths globally each year, including more than 1.6 million premature deaths among non-smokers exposed to second-hand smoke [1]. European Union policy documents have specifically identified hospitality workers as a particularly vulnerable occupational group where comprehensive protection is absent, because concentrations of tobacco smoke in bars

and restaurants can be high and exposure occurs during work [2]. Consequently, smoking regulation in hospitality is simultaneously a public-health issue, a hospitality-management issue and an OSH issue.

Croatian legal development is particularly relevant to OSH because protection of non-smokers at work was expressly regulated by the Occupational Safety Act as early as 1996, while subsequent tobacco-control legislation progressively introduced more detailed rules for enclosed public spaces and hospitality establishments [3-9]. The aim of this paper is to analyse the historical and legal evolution of smoking regulation in Croatian hospitality, with emphasis on occupational exposure, employer obligations, worker protection, enforcement and the practical limitations of technical measures such as ventilation. Cultural and economic considerations are discussed only where they are necessary to explain the development or implementation of the regulatory framework.

2. METHODOLOGY

This paper is a narrative review combined with a legal-historical analysis. The principal research question is how Croatian regulation of smoking in hospitality developed from general workplace protection of non-smokers into the present regulatory model and what this development means for the occupational exposure of hospitality workers.

Primary legal sources were prioritised. The legal analysis covered the Occupational Safety Act of 1996; the current Occupational Safety Act and its amendments; the pre-2008 tobacco-control framework; the Act on the Restriction of the Use of Tobacco Products of 2008 and its 2009 and 2013 amendments; the Act on the Restriction of the Use of Tobacco and Related Products of 2017; the 2018 amendment; and the 2025 amendments applicable to the legal position discussed in this paper [3-10]. Official texts in Narodne novine were used to verify the wording of provisions, dates of adoption and publication, transitional rules, amendments and the chronology of the legal framework. WHO, WHO FCTC and EU documents were used for international standards and OSH context, while Croatian Institute of Public Health (HZJZ) data and peer-reviewed or institutional historical literature were used for epidemiological and historical context [1, 2, 11-14].

The period examined extends from the early documented history of tobacco in Croatian territories to the legislation applicable in 2026, with detailed legal analysis concentrated on the period from 1996 onward. Each legislative stage was assessed according to four criteria: the scope of the smoking restriction; obligations imposed on employers or hospitality operators; permitted exceptions and technical conditions; and implications for worker exposure and enforcement. Secondary web pages, newspapers and lifestyle portals were not used to substantiate legal, epidemiological or statistical claims where primary or authoritative sources were available.

The approach has limitations. It is descriptive and doctrinal rather than experimental. The paper does not measure concentrations of second-hand smoke in Croatian hospitality establishments, does not independently quantify the economic effects of smoke-free legislation and does not perform a statistical analysis of inspection outcomes. Accordingly, claims concerning exposure, economic impact and enforcement effectiveness are limited to conclusions supported by the cited sources.

3. HISTORICAL DEVELOPMENT OF TOBACCO AND SMOKING

Tobacco originated in the Americas and was introduced into Europe after transatlantic contact. Over time, its use expanded from ritual and medicinal contexts into recreational consumption and, with industrial cigarette production, into a mass consumer practice. During the twentieth century, epidemiological and toxicological evidence increasingly established the association between tobacco smoke and serious disease. This transformed smoking from a predominantly private and cultural practice into an issue of public health and workplace protection [1].

In Croatian territories, tobacco has a documented history extending back several centuries. Dundović's review describes the historical development of tobacco cultivation, trade and regulation in Croatia and Bosnia and Herzegovina and demonstrates the long economic and social presence of tobacco in the region [12]. This historical embeddedness helps explain why later restrictions on smoking, especially in hospitality settings, represented not merely a technical regulatory change but also a change in established social practice.

The historical importance of tobacco should nevertheless be clearly separated from contemporary risk assessment. Cultural acceptance may explain resistance to regulatory change, but it does not reduce the health significance of second-hand smoke or the employer's obligation to manage workplace risks. This distinction is particularly important in hospitality, where the same enclosed space functions both as a social environment for guests and as a workplace for employees.

4. SMOKING IN HOSPITALITY: CULTURAL CONTEXT AND OCCUPATIONAL EXPOSURE

Cafés, restaurants and similar establishments have traditionally been important places of social interaction in Croatia. Smoking was historically associated with coffee, meals, conversation and leisure, and indoor tobacco smoke became normalised in many hospitality environments. Such cultural normalisation contributed to resistance when smoke-free measures were introduced. However, the interests of guests and the occupational position of employees are not identical.

A guest may remain in a venue for a limited period, whereas a waiter, bartender, cleaner, manager or other worker may spend an entire shift in the same indoor environment and may repeat that exposure over many working days. EU documents concerning smoke-free environments therefore identified hospitality workers as a particularly vulnerable occupational group in Member States without comprehensive protection [2]. This occupational dimension is central to the present analysis.

WHO FCTC Article 8 requires effective protection from exposure to tobacco smoke in indoor workplaces and indoor public places. The implementation guidelines state that no safe level of exposure to second-hand smoke exists and that engineering approaches such as ventilation, air exchange and designated smoking areas do not provide effective protection equivalent to a 100% smoke-free environment [11]. This is directly relevant to the Croatian hospitality model because Croatian legislation permits certain smoking rooms and smoking premises subject to detailed technical conditions.

From an OSH perspective, these technical conditions are legally prescribed engineering controls within defined exceptions, not evidence that the hazard has been eliminated. Eliminating indoor

smoking removes the exposure source, whereas ventilation and separation act only after smoke is generated. This distinction is consistent with WHO FCTC guidance favouring 100% smoke-free environments and is relevant when assessing legal compliance and residual worker risk [11].

5. REGULATION OF SMOKING IN THE HOSPITALITY SECTOR

Croatian regulation developed incrementally. The chronology is important because adoption, publication, transitional periods, amendments and the currently applicable provisions are not interchangeable. The following sections therefore distinguish the relevant legislative stages and their implications for hospitality workers.

5.1 Occupational Safety Act of 1996 - workplace protection of non-smokers

The Occupational Safety Act published in 1996 represented an important post-independence starting point for workplace protection from tobacco smoke. Article 63 required the employer to take appropriate measures to protect non-smokers from tobacco smoke, prohibited smoking at work meetings and prohibited smoking in work rooms and work areas except in places exceptionally designated by the employer and marked as smoking areas [3]. This provision is significant because the protected context was explicitly the workplace.

The 1996 framework thus established three elements that remain relevant to OSH analysis: an employer duty to protect non-smokers, a general prohibition in work areas and a limited possibility of designated smoking locations. It also provided for sanctions where employers failed to organise and ensure compliance. The original manuscript cited the current Occupational Safety Act for this historical claim; the present version corrects that mismatch by citing the 1996 Act itself [3].

5.2 Regulation before 2008

The development of tobacco-control legislation did not begin in 2008. The consolidated 2004 Act on the Restriction of the Use of Tobacco Products already defined hospitality premises as public spaces, prohibited smoking in certain hospitality categories and required smoking and non-smoking areas in establishments serving food. Smoking areas in other public spaces were limited in size and had to be equipped for ventilation [4].

This earlier model was based largely on spatial separation rather than complete elimination of indoor smoking. From an occupational perspective, such separation could protect some users of the premises while leaving employees exposed when their work required them to enter or remain in smoking areas. The distinction between customer zoning and worker exposure therefore predates the later comprehensive restrictions.

5.3 Act on the Restriction of the Use of Tobacco Products of 2008

The Croatian Parliament adopted the Act on the Restriction of the Use of Tobacco Products on 17 October 2008; it was published in Narodne novine 125/2008 on 29 October 2008 [5]. The Act introduced a broad prohibition on smoking in enclosed public spaces and prescribed obligations for owners and users of such spaces. Its transitional provisions gave owners and users of enclosed public spaces six months from the Act's entry into force to align their operations with the new requirements [5]. Therefore, the legislative date, entry into force and practical application to hospitality premises must be distinguished when describing the 2008-2009 transition.

For OSH purposes, the importance of the 2008 reform lies in the movement from partial zoning toward a much broader smoke-free rule. This substantially changed the regulatory environment of hospitality workplaces, even though the model was subsequently modified through amendments and exceptions.

5.4 Amendments in 2009 – regulated hospitality exceptions

The 2009 amendments revised the hospitality regime and created regulated exceptions [6]. The amended provisions permitted smoking rooms under specified conditions and allowed certain hospitality establishments that exclusively served beverages to designate the service area as a smoking area where statutory technical requirements were met. Requirements included separation from other areas, limitations on the size and use of smoking rooms and prescribed ventilation or filtration performance [6].

This compromise accommodated the operational characteristics of smaller cafés and bars, but it also preserved a category of workplaces in which employees could be occupationally exposed to second-hand smoke. Consequently, a legally compliant smoking premise and a smoke-free workplace are not synonymous. The distinction is central when evaluating the regulation from the standpoint of worker health.

5.5 Act on the Restriction of the Use of Tobacco and Related Products of 2017 and the 2018 amendment

In 2017, Croatia adopted the Act on the Restriction of the Use of Tobacco and Related Products (NN 45/2017), which aligned Croatian law with Directive 2014/40/EU in relevant areas and expanded regulation to related products [8]. Article 25 established the general prohibition on smoking tobacco and related products and on the use of electronic cigarettes and waterpipes in enclosed public spaces, subject to statutory exceptions. Articles 26-32 prescribed detailed conditions for smoking rooms and smoking premises, including physical separation, self-closing doors, an independent ventilation system, filtration, negative pressure of at least 5 Pa and prescribed air-supply conditions [8].

The 2018 amendment (NN 114/2018) primarily modified provisions concerning electronic cigarettes, refill containers and inspection competences; it did not fundamentally replace the hospitality smoking-room model established by the 2017 Act [9]. In parallel, the Occupational Safety Act was amended so that Article 57 expressly protects non-smokers from smoke from tobacco and related products and herbal products for smoking, as well as vapour from electronic cigarettes, and prohibits their use at the workplace except in a specially permitted and marked room or area [13]. This reinforces the need to read hospitality-specific exceptions together with general employer duties under OSH legislation.

5.6 Amendments of 2025 and the legal position applicable in 2026

The statement in the original manuscript that the 2018 amendments were “still current” is no longer accurate. In July 2025, Croatia adopted further amendments to the Act on the Restriction of the Use of Tobacco and Related Products (NN 98/2025) [10]. Among other changes, the amendments expressly included heated tobacco products in the prohibition applicable to enclosed public spaces and updated inspection powers and penalty provisions.

As applicable in 2026, the general prohibition in enclosed public spaces remains accompanied by statutory hospitality exceptions. Sanitary inspectors may order deficiencies in smoking rooms and smoking premises to be remedied, prohibit smoking where statutory conditions are not fulfilled and take further measures provided by law [10]. The current legal position should therefore be cited as the 2017 Act as amended in 2018 and 2025, rather than presenting the 2018 amendment as the latest legislative stage.

6. DISCUSSION: OCCUPATIONAL SAFETY AND HEALTH IMPLICATIONS

The legal history demonstrates a clear strengthening of protection from tobacco smoke, but it also reveals a continuing regulatory tension. Croatian OSH legislation places a duty on employers to protect non-smokers, while tobacco-control legislation permits smoking in defined hospitality settings when technical conditions are satisfied. In practice, this means that some hospitality workers may still perform work in an environment where the source of second-hand smoke has not been eliminated.

The technical requirements for smoking rooms are substantial and relevant for legal compliance. Physical separation, negative pressure, independent ventilation and filtration can reduce the migration of contaminated air into adjacent non-smoking areas [8]. Nevertheless, WHO FCTC Article 8 guidance is explicit that ventilation, air exchange and designated smoking areas do not protect against exposure in the same manner as a 100% smoke-free environment [11]. The scientifically and legally precise formulation is therefore that Croatian technical measures regulate and may reduce exposure pathways, but they should not be described as eliminating the health risk of second-hand smoke.

Employer obligations should also be viewed through the general preventive principles of the Occupational Safety Act. The employer must organise and implement occupational safety with prevention of risks in mind and ensure the highest possible level of worker protection, while Article 57 specifically addresses protection of non-smokers [13]. For hospitality employers, this supports integrating smoke-related exposure into risk assessment, worker information, work organisation, maintenance of ventilation systems, verification of statutory conditions and procedures for responding to complaints or identified non-compliance.

Enforcement requires similarly careful interpretation. The existence of substantial fines or inspection powers does not by itself prove that enforcement is effective. A conclusion about effectiveness would require systematic data on inspection frequency, detected violations, repeat violations, corrective measures and compliance trends. Because this review does not independently analyse such a dataset, the earlier claim that financial penalties were demonstrably insufficient has been removed. The supported conclusion is that Croatian law provides inspection and sanctioning mechanisms, while their practical effectiveness requires separate empirical evaluation [10].

Economic claims must be treated with the same caution. Adaptation to technical requirements may entail costs for hospitality operators, including construction, ventilation, filtration, monitoring and maintenance. However, the present review does not quantify those costs and therefore does not claim that smoke-free rules cause an overall loss of revenue or a general negative economic effect. EU evidence cited in the development of smoke-free policy reported that comprehensive smoke-free policies can improve hospitality workers' respiratory health and had not been shown to harm the economy overall [2].

The central OSH finding is therefore that formal compliance and prevention of occupational exposure are related but not identical. A hospitality establishment may satisfy the statutory technical conditions for a smoking room while residual occupational exposure remains possible. Where work can be organised without indoor exposure, elimination of the source remains the more protective preventive approach. This conclusion is consistent with the WHO FCTC principle of comprehensive protection from tobacco smoke [11].

7. CONCLUSION

The history of smoking regulation in Croatian hospitality shows a progression from social normalisation and partial restrictions toward a detailed legal framework combining general workplace protection with hospitality-specific exceptions. The 1996 Occupational Safety Act already required employers to protect non-smokers and restricted smoking in work areas. The pre-2008 tobacco-control framework used partial prohibitions and zoning, while the 2008 reform introduced a broader smoke-free rule. The 2009 amendments created regulated hospitality exceptions, the 2017 Act retained and technically specified those exceptions, and the 2025 amendments updated the framework and expressly included heated tobacco products.

The principal occupational-safety conclusion is that hospitality workers should be treated as a distinct exposure group rather than merely as members of the public. Their exposure may be repeated, prolonged and directly connected with the performance of work. Croatian technical requirements for smoking rooms and smoking premises are important for legal compliance, but international guidance does not regard ventilation, filtration or designated smoking areas as equivalent to a fully smoke-free workplace.

Future evaluation of Croatian policy should therefore distinguish three questions: whether a hospitality establishment formally complies with the applicable Act; whether inspection and enforcement secure consistent compliance; and whether the permitted model provides the level of worker-health protection expected under contemporary OSH principles and WHO FCTC Article 8. Further Croatian research should use occupational-exposure measurements and systematic inspection data to answer these questions empirically. On the evidence reviewed here, eliminating indoor exposure wherever work is performed remains the most protective preventive approach.

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Original scientific paper

EXPERIENCES OF WOMEN IN RECRUITMENT PROCESSES FOR THE POSITION OF OCCUPATIONAL HEALTH AND SAFETY SPECIALIST IN THE REPUBLIC OF CROATIA

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Abstract: *Equal employment conditions and non-discriminatory selection procedures are an important part of lawful and transparent recruitment. This paper provides a brief overview of the legal framework governing the prohibition of discrimination in the field of employment. The empirical part of the paper is based on a survey conducted in 2021 among women who are employed or were seeking employment for the position of occupational health and safety specialist in the Republic of Croatia. The data were collected through an online questionnaire (N = 121) and analyzed using descriptive statistical methods. The research included questions about respondents' experiences when applying for job vacancies, communication with employers, and their experiences during job interviews. The results provide insight into the respondents' experiences in recruitment processes and highlight the importance of consistent application of the legal framework and professional standards in selection procedures in the field of occupational health and safety.*

Keywords: *occupational health and safety, employment, female occupational health and safety specialists.*

1. INTRODUCTION

Gender equality is one of the highest values of the constitutional order of the Republic of Croatia, yet empirical evidence shows that this value is not fully realised in labour market practice [1]. According to the most recent Gender Equality Index of the European Institute for Gender Equality, the European Union as a whole scores 63.4 out of 100 points, and women in the EU earn on average

77% of men's annual earnings, meaning they would need to work fifteen and a half months to match men's yearly pay [2]. A World Bank analysis shows that Croatia, despite progress in certain areas, remains among the lower-ranked EU member states in overall gender equality, with a particularly pronounced gap in the domain of power and decision-making [3].

The occupation of OHS specialist in Croatia is formally gender-neutral, yet the professional environment in which this occupation is exercised (industry, construction, transport, energy) remains strongly gender-segregated in favour of men. The European Agency for Safety and Health at Work (EU-OSHA), in its review of employment trends and their impact on women's OSH, reports that the EU gender employment gap stood at 10.7 percentage points in 2022, and that women in OHS-related professions remain significantly under-represented in managerial and expert positions despite a growing share of highly educated women [4].

In this context, the aim of this study was to determine whether gender discrimination against women exists in the Republic of Croatia during recruitment for the position of OHS specialist, how prevalent it is, and which forms are most common.

The main hypothesis (H1) is that women are in a less favourable position than men when seeking this employment for the position of OHS specialist in Croatia; this is examined through three specific aspects of discrimination - in the criteria and selection of candidates (H1a), based on reproductive status, including motherhood, pregnancy and childbearing intentions (H1b), and rooted in prejudice and stereotypes about gender roles and abilities (H1c).

This paper contributes to the current scientific debate in two ways. First, existing Croatian literature on the “glass ceiling” and occupational gender segregation mostly concerns the science and higher-education sector [5, 6] or managerial positions in the economy in general [7, 8], while data on the OHS profession in the Croatian context are almost entirely absent. Second, the paper links national findings to the most recent European legislative framework - Directive (EU) 2023/970 on pay transparency [9], which acquired direct legal effect in member states, including Croatia, as of 8 June 2026, despite national legislation not yet being formally aligned [10].

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1. Legal Framework for the Prohibition of Discrimination

The prohibition of gender-based discrimination in the Republic of Croatia is regulated at several levels. The Constitution of the Republic of Croatia [1] declares gender equality one of the highest values of the constitutional order (Art. 3) and guarantees rights and freedoms regardless of sex (Art. 14). At the statutory level, this is elaborated by the Anti-Discrimination Act [11], the Gender Equality Act [12], and the Labour Act [13], while the Occupational Safety and Health Act [14] regulates the profession itself..

At the European Union level, the fundamental legal source is Directive 2006/54/EC on the implementation of the principle of equal opportunities and equal treatment of men and women in matters of employment and occupation. This framework was significantly strengthened in 2022 and 2023 by two new directives not yet addressed in existing Croatian literature on this topic: Directive (EU) 2022/2381 on improving the gender balance among directors of listed companies, which prescribes a quota of 40% of non-executive or 33% of all board members of large listed companies

by 30 June 2026 [15], and Directive (EU) 2023/970 on strengthening the application of the principle of equal pay for equal work or work of equal value through pay transparency and enforcement mechanisms, which introduces a ban on asking candidates about previous pay, the right to information on the pay range before a job interview, and an obligation for gender-neutral criteria for setting and advancing pay [9]. As the Republic of Croatia did not meet the transposition deadline for Directive (EU) 2023/970 (7 June 2026), its sufficiently clear and unconditional provisions have had direct horizontal effect since 8 June 2026, which employees may invoke directly [10].

2.2. The Glass Ceiling Concept

Explanations of occupational gender segregation and recruitment discrimination in Croatian literature are most commonly linked to the "glass ceiling" - an invisible but persistent barrier preventing women's advancement despite equal or better qualifications [6]. It operates through subtler mechanisms than formal barriers - informal decision-making networks, stereotyped assessments of "suitability" for demanding roles, and implicit expectations about balancing professional and family duties - and is complemented by the related notion of the "sticky floor", describing women's retention in lower, lower-paid positions without realistic prospects of advancement.

In a more recent Croatian study, Burušić-Barčan and Burušić confirm that occupational gender segregation in Croatia continues to allocate better-paid managerial positions to men despite educated women's demonstrated ambition and knowledge, showing the glass ceiling remains empirically grounded rather than an outdated concept [8]; similar patterns have long been recorded in science and higher education [6]. This persistence across different sectors suggests a structural rather than sector-specific problem, one not previously examined systematically in the OHS profession.

2.3. Women in OHS Professions - Prior Research

International literature on the gender dimension of occupational safety and health has been significantly strengthened in recent years. EU-OSHA, in its review of the impact of employment trends on women's OSH, warns that the risks faced by female workers are systematically underestimated because safety standards and risk research have traditionally been shaped around male work experience [4]. EU-OSHA further extended the focus to the gender dimension of telework, showing that hybrid work models disproportionately affect women due to the overlap of paid work and unpaid care [16]. Ledda, Duclos and Martínez-Jarreta, in the editorial introduction to a special issue devoted to women in occupational health science, note that the share of women among STEM researchers, including occupational medicine, remains below 30%, despite a growing number of successful women scientists in the field [17]. Methodologically related to this study, Kelemenić-Dražin et al. conducted a survey on barriers to career progression among Croatian oncologists compared with the international ESMO survey, confirming that gender barriers to advancement in highly skilled medical and technical professions in Croatia can be reliably measured using survey methodology similar to that applied in this study [18].

At the national level, the Croatian Bureau of Statistics [19] and the Ombudsperson for Gender Equality [20] regularly monitor the gender pay gap, which according to DZS methodology stood at 6.8% for 2023/2024, while Eurostat methodology recorded a gap of 7.4% for the same period [21]. These methodological differences further highlight the need for caution when interpreting aggregate discrimination indicators and justify the use of qualitatively richer, profession-focused survey research such as this one.

3. RESEARCH METHODOLOGY

3.1. Instrument and Procedure

Data were collected through an online questionnaire designed in LimeSurvey. The questionnaire consisted of three thematic sections: (1) socio-demographic characteristics of respondents (9 questions), (2) respondents' experiences related to job advertisements, job interviews and the workplace (19 questions), and (3) respondents' attitudes toward the position of women in OHS professions in Croatia, measured on a Likert-type scale from 1 (strongly disagree) to 5 (strongly agree) (4 groups of statements). The survey was conducted between 3 and 27 June 2021. The questionnaire was completely anonymous and distributed via the social networks Facebook Messenger and LinkedIn.

3.2. Sample

A total of 179 respondents accessed the survey, of which 58 questionnaires were partially completed and 121 fully completed (completion rate 67.6%). The final sample therefore comprises 121 fully completed questionnaires. This is a convenience (purposive) sample collected using the snowball method via professional social networks, which represents a methodological limitation, as it does not allow generalisation of findings to the entire population of women employed in or interested in employment in the OHS profession in Croatia. All respondents in the sample identified as women.

3.3. Data Analysis Methods

The collected data were processed using descriptive statistics (absolute and relative frequencies) in Microsoft Excel and presented in tables and charts. For the interpretation of Likert scales, ratings 1 and 2 were interpreted as disagreement with the statement, rating 3 as neutral, and ratings 4 and 5 as agreement with the statement. The paper does not include inferential statistical analysis (e.g., chi-square test or non-parametric tests of differences by age, sector, or length of service), which represents a methodological limitation and a direction for future research, elaborated in section 5.4.

4. RESULTS

4.1. Socio-demographic Characteristics of the Sample

The sample consists exclusively of women, most aged 18-30, holding a university (58.83%) or professional higher-education (27.73%) degree. Most respondents are currently employed (90.77%), predominantly in the public sector (68.91%), with relatively short professional tenure (57.98% under 5 years), consistent with OHS being a relatively young regulated profession in Croatia; 34.45% have one or more children.

4.2. Discriminatory Practices in Recruitment and at the Workplace

Table 1 summarises key indicators of exposure to discriminatory practices during the recruitment process and at the workplace. The most pronounced finding relates to questions about marital status and number of children, to which 62.79% of respondents were ever exposed, despite such questions

being explicitly prohibited by the Labour Act, the Gender Equality Act and the Anti-Discrimination Act. Similarly, 46.28% of respondents had ever been asked about childbearing intentions and family planning - a question that constitutes a direct violation of Art. 30 of the Labour Act (prohibition of unequal treatment of pregnant workers).

Table 1: Indicators of exposure to discriminatory practices (N = 121)

Indicator of discriminatory practice	% of respondents with experience	Note
Encountered a gender-discriminatory job advertisement (ever)	37.19%	once, several times, or very often
Asked about marital status / number of children in an interview (ever)	62.79%	sum of all categories except “never”
Asked about childbearing intentions / family planning (ever)	46.28%	prohibited under the Labour Act
Other private-life questions in a job interview	38.02%	e.g., about spouse, pets, place of residence
Less favourable treatment compared to a male candidate (ever)	53.72%	sum of categories confirming the experience
Dismissal due to pregnancy (once or more)	6.62%	of respondents who had ever been pregnant
Rejected at interview due to pregnancy planning	8.27%	once or more
Learned that a less qualified male candidate was hired	39.67%	“once” + “several times”
Experience of sexual harassment (without filing a lawsuit)	21.49%	0% of respondents filed a lawsuit

Source: authors' research

Regarding the outcomes of application procedures, 42.15% of respondents who received feedback from an employer cited “a more competent candidate was selected” as the reason for rejection, while 4.13% cited an explicitly gender-based reason (“you are not able to perform the required tasks as a woman”), and 0.83% an explicitly discriminatory reason related to pregnancy. Although a minority share, these findings represent direct, documented examples of anti-discrimination legislation being violated by employers. Furthermore, 39.67% of respondents had ever learned that a male candidate with fewer formal qualifications was hired for the position they applied for, which is a direct indicator of gender-biased decision-making in recruitment.

4.3. Sexual Harassment and (Non-)Use of Legal Protection

A total of 21.49% of respondents reported experiencing sexual harassment, while none of the respondents in the sample filed a lawsuit against an employer, and 2.48% stated they would have filed a lawsuit had they known they were legally entitled to do so. Among respondents who considered legal protection but did not pursue it, the most frequently cited reason was distrust in the judicial system (17.36%), followed by fear of consequences for future employment (12.40%), slowness of the judiciary (7.44%), lack of financial resources (6.61%), and lack of information about their rights (3.31%). This pattern - a high non-reporting rate despite existing experience of harassment - is consistent with broader findings by the Ombudsperson for Gender Equality [20] regarding structural barriers to legal protection for victims of discrimination in Croatia.

4.4. Perceptions of the Position of Women in the OHS Profession

Table 2 shows the degree of agreement of respondents with key statements about the position of women in the OHS profession, measured on a Likert scale. The most pronounced finding is that as many as 88.44% of respondents believe that men find it much easier to gain employment in OHS in Croatia than women, while at the same time 90.00% believe that women and men should have equal employment and advancement opportunities in all professions. This combination - high awareness of existing inequality alongside a strong normative commitment to equality - suggests that respondents are simultaneously exposed to discrimination and aware of its injustice, consistent with the original study's conclusion regarding respondents' "gender awareness" of their own discrimination [22].

Table 2: Degree of agreement with selected statements on the position of women in the OHS profession (N = 121)

Statement (Likert scale 1-5)	% agreement / disagreement
Men find it much easier to get a job in OHS in Croatia than women	88.44% (agreement)
Women should not be excluded from so-called "male" jobs because of their sex	76.04% (agreement)
Women and men should have equal employment and advancement opportunities in all professions	90.00% (agreement)
Women in Croatia will still need to fight hard for real equality in OHS jobs	69.75% (agreement)
Women in OHS jobs are economically disadvantaged compared to men	49.59% (agreement)
Women and men in OHS jobs do not have equal status in society	43.80% (agreement)
Women and men in OHS jobs do not have equal benefit from work results	54.16% (agreement)
Women and men do not have equal employment opportunities in OHS jobs	56.66% (agreement)
Women mostly achieve business success through their sexual qualities (stereotype)	77.12% (disagreement with the stereotype)
Career advancement for women does not happen without sexual favours (stereotype)	75.21% (disagreement with the stereotype)

Source: authors' research

Notably, respondents rejected gender stereotypes portraying women as reliant on "sexual qualities" for career advancement (77.12% disagreement) or as unable to advance without "sexual favours" (75.21% disagreement), thereby clearly distinguishing recognition of structural discrimination from acceptance of sexist stereotypes about the causes of women's (lack of) success in the profession.

5. DISCUSSION

5.1. Confirmation of Hypotheses

The research findings confirm the main hypothesis (H1) that women are in a less favourable position than men when seeking employment for the position of OHS specialist in Croatia - this is indicated both by respondents' subjective perception (88.44% believe men find it easier to get a job) and by objective indicators of unlawful employer conduct (62.79% of respondents were ever asked about marital status/number of children; 39.67% learned of a less qualified male candidate being hired).

Specific hypothesis H1a on discrimination in candidate criteria and selection is also confirmed, as indicated by data on the hiring of less qualified male candidates and explicitly gender-based employer responses to job applications. Hypothesis H1b on discrimination based on reproductive status is likewise confirmed - despite an absolute legal prohibition, almost half of the respondents (46.28%) were ever asked about childbearing intentions, and a small but non-negligible share directly experienced dismissal or rejection related to pregnancy. Finally, hypothesis H1c on discrimination due to prejudice and stereotypes is confirmed through the high share of respondents reporting less favourable treatment compared to male candidates (53.72%) and the belief that systemic gender inequality exists in access to business opportunities.

5.2. Comparison with Prior Research

The findings of this study are consistent with Burušić-Barčan and Burušić, who conclude that occupational gender segregation in Croatia systematically allocates better-paid and managerial positions to male colleagues despite women's equal or better qualifications [8]. The finding that 39.67% of respondents learn of less qualified male candidates being hired directly confirms the mechanism described by Nidogon Višnjić, Begičević Ređep and Vidaček-Hainš as the perception of systemic gender bias in recruitment and promotion decisions [7].

Compared with international literature on women in OHS, the findings of this study support EU-OSHA's [4] conclusions that women in OHS-related professional fields continue to face structural barriers not solely attributable to differences in qualifications. The high non-reporting rate of sexual harassment (0% of the 21.49% of respondents who experienced it filed a lawsuit) mirrors the pattern recorded by Kelemenić-Dražin et al. among Croatian oncologists - an absence of formal complaints despite documented experience of discrimination - suggesting a structural, rather than isolated, problem of trust in institutional protection mechanisms across Croatian highly skilled professions in general [18].

The findings can also be interpreted as a reflection of the glass ceiling within a traditionally male-dominated field (industry, construction, energy): women OHS specialists operate in an environment where they are more exposed to heightened visibility and pressure to prove competence - a pattern reflected in this study by the high share of respondents (69.4%) who feel fully physically and mentally capable of performing the job, despite simultaneously high perceived discrimination.

5.3. Policy and Practice Implications

The research findings have direct implications for the forthcoming implementation of Directive (EU) 2023/970 on pay transparency within the Croatian legal system [9]. Given that 62.79% of respondents were ever exposed to unlawful questions about marital status, introducing the obligation of gender-neutral, predefined criteria for recruitment and pay determination (Arts. 5-7 of the Directive) could significantly reduce the scope for discretionary, potentially discriminatory employer decision-making in this profession. Similarly, the obligation to inform candidates of the pay range before a job interview could reduce indirect discrimination in pay negotiations, which is also indicated by findings on the perceived economic disadvantage of women in the profession (49.59% of respondents).

It is also recommended to systematically monitor compliance with the prohibition on asking private-life questions during job interviews, for example through standardised HR forms and employer training in the OHS sector, as well as to strengthen trust in institutional protection mechanisms (the Ombudsperson for Gender Equality, the courts), given that distrust in the judicial system is the most frequently cited barrier to reporting discrimination in this sample.

5.4. Limitations and Directions for Future Research

This study has several limitations. The non-representative convenience sample, recruited via snowball sampling and excluding male and employer perspectives, limits the generalisability of findings and prevents comparison across stakeholders in the recruitment process. Reliance on descriptive statistics and a cross-sectional design further restrict the ability to test statistical significance or track change over time; future research should therefore apply inferential methods, such as chi-square tests by age, sector or tenure, and a longitudinal design, for example comparing with 2026 data on the implementation of Directive (EU) 2023/970, ideally complemented by a qualitative component such as semi-structured interviews to gain deeper insight into the mechanisms of discrimination described in respondents' open-ended answers.

6. CONCLUSION

The aim of this study was to determine whether gender discrimination against women exists in the Republic of Croatia during recruitment for the position of OHS specialist. The results of a survey conducted on a convenience sample of 121 respondents confirm the main hypothesis regarding the less favourable position of women compared to men, as well as all three specific hypotheses - on discrimination in candidate criteria and selection, discrimination based on reproductive status, and discrimination based on gender prejudice and stereotypes.

The findings show that, despite a clear legal framework prohibiting gender-based discrimination (the Constitution, the Anti-Discrimination Act, the Gender Equality Act, the Labour Act), recruitment practice in the OHS profession in Croatia still contains elements of direct and indirect discrimination, ranging from unlawful interview questions to the absence of formal legal protection for victims of sexual harassment. At the same time, the high level of agreement among respondents with the normative position on the need for gender equality (90.00%) shows that discrimination does not stem from a lack of awareness among victims, but from structural and institutional barriers to reporting and sanctioning it.

This paper contributes to Croatian and international literature on gender (in)equality in the labour market by directing attention to the hitherto under-researched professional field of occupational safety and health, and by linking national empirical findings to the most recent European legislative developments, in particular Directive (EU) 2023/970 [9] on pay transparency, whose future implementation within the Croatian legal system could directly address several forms of discrimination observed in this study. It is recommended that future research expand the sample, include inferential statistical analysis, and monitor the effects of forthcoming legislative changes on the actual position of women in this and related technical professions.

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Professional paper

RESCUE ON FAST-WATER RIVERS AND IN FLOOD CONDITIONS: THE CASE OF KARLOVAC COUNTY

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Abstract: *This paper addresses the topic of rescue operations on fast-moving waters and in flood situations, with particular emphasis on Karlovac County, one of the most flood-prone areas in Croatia when it comes to flooding and flash floods. The county is intersected by rivers such as the Kupa, Korana, Mrežnica, and Dobra, which, during heavy rainfall and snowmelt, often overflow their banks and threaten the local population, property, and transport infrastructure. The paper analyzes the main risks and challenges faced by members of fire brigades, the Croatian Mountain Rescue Service (HGSS), civil protection units, and other operational forces during rescue operations in flooded and fast-flowing areas. Particular attention is given to the organization of the rescue system, the necessary equipment, rescuer training, and the importance of cooperation between local authorities and state services. Based on specific examples of interventions in Karlovac and the surrounding areas, it is concluded that effective rescue operations are possible only through timely coordination, continuous training, and the availability of specialized equipment.*

Keywords : *Swift-water rescue, flooding, Karlovac County*

1. INTRODUCTION

The subject of this paper is the system of rescue operations on wild waters, with particular emphasis on the area of Karlovac County, which is one of the most river-rich areas in Croatia in terms of the number and diversity of its rivers. The Kupa, Korana, Mrežnica, and Dobra rivers, which flow through this region, offer many benefits but also represent a potential threat to human safety, particularly during high water levels and adverse weather conditions. The aim of this paper is to analyze the existing wild-water rescue system in Karlovac County, identify the key challenges faced by rescue services, and propose possible measures to improve the efficiency and safety of rescue operations. (Arial 10 pt)

2. RISKS AND HAZARDS ON WATER AND DURING FLOODS

2.1. Principles and Physiology of Rescue

For the successful implementation of rescue operations in flood and fast-water situations, four interconnected elements are essential:

- Education and training
- Continuous practice
- Acquired experience
- Decision-making ability

The first step toward effective rescue operations is professional training. Teams must complete specialized courses in order to acquire the necessary knowledge and techniques. However, theory alone is not sufficient—it is necessary to regularly practice acquired skills through simulations and practical exercises, particularly at locations that have previously been identified as high-risk areas.

Over time, and through repeated application of knowledge in real or simulated conditions, rescuers gain valuable experience. This experience helps them recognize patterns in water behavior, identify terrain hazards, and assess the effectiveness of different rescue methods. Through practice and experience, what may be the most important ability of all is developed—judgment. This ability enables a team to make correct decisions quickly in complex and unpredictable situations. Judgment is based on understanding what works, what presents a risk, and how to optimize a rescue operation without unnecessary loss of time.

It is important to note that this ability cannot be learned from a book or developed quickly—it is built gradually through years of work and exposure to different challenges in the field.

In all rescue situations, the order of priorities for every rescuer should be clear:

- Personal safety
- Team safety
- Rescue of the casualty

Responsibility for one's own actions is extremely important. If a rescuer is inadequately trained or does not have appropriate equipment, an intervention can become dangerous and result in additional casualties. Water rescue should begin only after the rescuer has ensured their own safety as well as the safety of the team members. Every intervention must be carried out within the capabilities and competencies of the team—exceeding these limits can endanger everyone involved. Once the people involved have been secured and there is no longer an immediate risk, equipment can be recovered; however, it should always be remembered that equipment is replaceable, whereas human lives are not.

Floods

Although working in flood conditions has many similarities to working in other aquatic environments, it also presents specific challenges and additional water-related hazards.

River water levels can change significantly depending on weather conditions such as rainfall, snowmelt, or the release of water from reservoirs and dams. Nevertheless, most of the time a river remains within the boundaries of its river channel, meaning that its direction and behavior are generally predictable. When the water level rises to the point where the river channel can no longer contain the entire volume of incoming water, the river begins to overflow its banks. The water then spreads into surrounding, often low-lying areas, turning them into flooded terrain.

An increase in the amount of water in a river means that existing hazards, such as dams and eddies, become even more pronounced and dangerous, even if the structures themselves have been damaged or washed away. In addition, new hazards may appear. Areas where the water was previously deep enough only for boats may now be covered by flowing water across roads or obstacles that were never intended to form part of the watercourse.

In such situations, objects carried by the water pose a significant threat—for example, vehicles, containers, traffic signs, pieces of furniture, or park benches. During floods, water often carries large amounts of debris that can become trapped against structures such as houses and bridges. This can cause structural damage and pose a serious threat to people in the water.

When water flows across floodplains, the risk of contamination by hazardous substances such as sewage, pesticides, and agricultural waste increases. It is important to note that when a river leaves its channel and spreads across a floodplain, the flow may visibly slow down. However, within the original river channel, the water maintains its usual speed.

Floods generally develop through four basic phases. Each flood progresses through these phases at a different rate because no two floods are identical:

- Phase 1 – Pre-flood preparation
- Phase 2 – Rapid water surge (flash flood)
- Phase 3 – Flood expansion
- Phase 4 – Recovery and return

3. COMMUNICATION

In rescue operations, effective communication is a key component that can often make the difference between success and failure. Without reliable and clear transmission of information among team members, as well as between the team and command, there is a significantly greater risk of errors that may jeopardize the success of the mission.

Communication can be achieved in several ways—verbally, through spoken commands, or through visual signals. However, modern operations increasingly rely on technical communication equipment, such as handheld radios. In such cases, it is essential to have a backup option in the event of equipment failure or depleted batteries. Relying on a single method of communication represents a serious safety risk.

Regardless of the system used, communication must be familiar and understandable to all team members. Confirmation that a message has been received is essential for preventing misunderstandings, particularly in demanding and noisy environments such as riverbanks. Such

environments make verbal communication even more difficult, which is why it is crucial that messages are short, clear, and precise.

Ultimately, effective communication is based on simplicity, reliability, and the ability to adapt to circumstances. Its preparation and regular practice must therefore be an integral part of every serious rescue operation.

3.1. SEARCH

The first stage of a fast-water rescue operation is locating the casualty. In many cases, this can be the most difficult stage. A search is an emergency situation: a person is missing and may be injured. The search process is highly organized and systematic. Search areas and routes are carefully planned in order to maximize the chances of success. It is important that searchers follow their designated routes.

Natural river channels and flooded areas contain a large number of potential hiding places. In addition, limited access and high water velocity can make searching difficult and time-consuming. Searches for many casualties involved in fast-water and flood incidents can last for a considerable amount of time. Searches may also have to be conducted at night or in unfavorable weather conditions. This makes the operation more difficult and increases the potential risks to the searchers. Searching large flood areas can become a multi-day operation, and in addition to exhausting searchers, it creates specific management challenges. [6]

Searching is much more complicated than simply driving around looking for something. Active searching is mentally exhausting and physically demanding work. Searchers should imagine themselves positioned at the center of a cube. They must look forward at near, medium, and long distances. They must also look to the left, right, behind, below, and above at the same three distances.

The size of the cube will vary depending on the riverbank terrain and aquatic environment. Ideally, the search area covered by one boat should overlap with that of another boat to ensure that there is no possibility of overlooking a particular area. [6]

The environment must not be so challenging that searchers are forced to concentrate solely on their own survival. If searchers are only surviving, they are not searching. The environment must remain within the capabilities and experience of the search team. [6]

4. EXAMPLE OF A RESCUE OPERATION ON THE KUPA RIVER

On the Kupa River, in the vicinity of Karlovac, a rescue operation was carried out involving a migrant who had nearly drowned. Due to the strong current, high water level, and low water temperature, the operation was extremely demanding.

The casualty had spent approximately half an hour in the water and was suffering from hypothermia and shock. The person could not swim and was trapped against an obstacle, specifically a strainer, while firmly holding onto a tree. During the rescue operation, all the hazards previously described in this paper were taken into consideration, and the aforementioned swimming and rescue techniques were applied.

When a person is injured and remains trapped in water while the current is so strong that they are unable to free themselves, the situation becomes extremely complex and dangerous. In such circumstances, time is of critical importance.

However, the order of priorities in every rescue operation is:

- Rescuer
- Team
- Casualty
- The stages of the rescue operation are as follows:
- Locate the person
- Approach the person
- Stabilize the situation
- Bring the person to safety

Due to the nature of such situations, rescuers can easily become exposed to danger. Before any action begins, all potential hazards must be assessed. Considering the severity of the situation and the number of available solutions, the team leader must take control of the operation and clearly communicate the plan to the other team members.

The most important initial objective is stabilization—maintaining the casualty's airway and thereby gaining additional time to continue the rescue operation.

One of the safer stabilization methods is the use of support ropes. A rope is brought to the trapped person. Although positioning it underneath the person's body is not always easy, if successful, it can provide significant assistance. Once the rope has been positioned, it can be used to attach additional equipment or to lift the person, thereby facilitating their release and the provision of assistance.

Due to the specific circumstances and the inability to swim to the casualty, a technique involving securing the boat and rowing toward the casualty was used. Since the person was unable to hold onto a rope, a boat-based rescue technique was employed. The casualty was pulled into the boat and then brought safely to the riverbank.

As the casualty was suffering from hypothermia and shock, they were warmed and subsequently handed over to emergency medical personnel. The rescue operation was thereby successfully completed.

5. ANALYSIS OF THE EXERCISE ON THE KUPA AND CETINA RIVERS

During exercises conducted on the Kupa and Cetina rivers and through the use of various rescue techniques, their differences can be clearly observed. They differ significantly in their natural and geographical characteristics, which directly affects the approach to rescue operations and the challenges encountered.

The Kupa River flows through the northwestern part of Croatia, mainly through lowland and hilly areas. In its mountainous section, its flow is moderately fast, while in the lowland areas it slows considerably. In most cases, access to the riverbank is relatively easy, which facilitates rescue operations from land or by boat.

Water temperature varies, but hypothermia is generally not as pronounced as in some other rivers, except during colder months. During periods of heavy rainfall, there is a significant possibility of flooding and the river overflowing its banks

On the other hand, the Cetina River flows through Dalmatia and is known for its rugged karst landscape, canyons, and rapids. The water in the Cetina is extremely cold throughout the year, with the spring having a temperature of approximately 7°C. The river has a fast current, numerous waterfalls, underwater obstacles, and narrow passages. These characteristics make rescue operations extremely demanding and often dangerous.

Access to casualties is frequently difficult and requires technical equipment for work at height and depth. Rescuers must possess specialized experience and skills. The upper section of the Cetina River is not navigable due to the terrain and the presence of a hydroelectric power plant.

A common factor for both rivers during the summer months is the large number of swimmers, rafters, and canoeists.

In conclusion, rescue operations on the Kupa River most often involve conventional interventions in conditions that are more accessible and less extreme. In contrast, the Cetina River requires a high level of preparedness, technical equipment, and the presence of specialized teams, often including mountain rescue personnel or divers.

These differences must be clearly understood in order to approach each situation in the most effective and safest possible manner.

6. CONCLUSION

Rescue operations on wild waters in Karlovac County are an extremely important activity that requires a high level of preparedness, coordination, and expertise. Given that the county is rich in rivers such as the Kupa, Korana, Mrežnica, and Dobra, which are popular destinations for recreational users, athletes, and tourists, the risk of water-related accidents is always present.

Changing weather conditions, strong currents, waterfalls, and inaccessible terrain further complicate rescue operations. For this reason, emergency services such as fire brigades, emergency medical services, the police, and members of the Croatian Mountain Rescue Service (HGSS) play a crucial role. The success of an intervention often depends on a rapid response, knowledge of the terrain, and the proper use of specialized equipment.

Prevention is also important, particularly educating citizens and, above all, those who participate in water-based activities.

Given its geographical characteristics and the risks associated with its rivers, Karlovac County must continue investing in the training and equipment of rescue services, as well as in the development of systems for coordination and cooperation among all relevant stakeholders.

Only through a coordinated approach and continuous improvement of the system will it be possible to effectively reduce the number of accidents and increase the safety of all users of wild waters.

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Professional paper

FRAMEWORK AND BASIS FOR REGULATING, IMPLEMENTING, AND MONITORING OCCUPATIONAL SAFETY AND HEALTH IN NAUTICAL TOURISM

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Abstract: *The paper analyzes the occupational safety and health (OSH) system within the specific conditions of nautical tourism in the Republic of Croatia, focusing particularly on labor processes conducted on the maritime domain (marinas, anchorages, berths, and dry marinas). The main objective of the research is to determine the role and importance of autonomous general acts of employers in compensating for the shortcomings of direct heteronomous, i.e., statutory regulation. Utilizing a multi-methodological approach rooted in qualitative methods of scientific and professional analysis (normative method, content analysis, comparative method), three tiers of sources were examined: heteronomous regulations, autonomous acts (statutes, collective agreements, rulebooks), and professional studies or internal documents of employers (risk assessments, evacuation plans). The research revealed a crucial legislative gap – state regulations do not contain provisions that directly address the specific risks and rights of workers within nautical tourism activities at sea. The results demonstrate that the focus of legal regulation is justifiedly shifted to autonomous law, within which the corporate statute, collective agreement, and specialized rulebooks operationally implement safety measures, fire protection systems, and specific personal protective equipment. The paper proves that the overall effectiveness of the OHS system in this sector directly depends on the quality and up-to-dateness of the autonomous acts enacted by the concessionaire employers.*

Keywords: *nautical tourism, work in marinas, occupational safety, autonomous law, maritime domain.*

1. INTRODUCTION

Nautical tourism is an expanding activity. In the Republic of Croatia, it is classified under tourism activities. This paper primarily focuses on labor and labor relations, specifically detailing the occupational health and safety of individuals performing these activities for employers who hold concessions on maritime domains in marinas and other facilities defined by regulations (anchorages,

moorings, dry marinas, and other facilities). Work is performed on and by the sea (closer to or further from the coast) under specific working conditions (organizational, economic, technical-technological, social, legal, and other legal characteristics).

2. RESEARCH METHODOLOGY

2.1. Research Objective

The main objective of the research is to analyze the occupational safety and health system within the specific conditions of nautical tourism in the Republic of Croatia. Emphasis is placed on the role, content, and importance of autonomous general acts (statutes, collective agreements, rulebooks, and risk assessments) in compensating for the shortcomings of direct heteronomous, i.e., statutory regulation.

2.2. Subject and Sample of the Research

The subject of the research encompasses legal relations, obligations, responsibilities, and concrete occupational safety measures implemented under specific conditions on the maritime domain by employers (concessionaires) in marinas, tourist berths, anchorages, and dry marinas. The sample of documents used in the analysis consists of three tiers of sources:

- Heteronomous regulations – The Constitution of the Republic of Croatia, national legislation, and secondary sources of European Union law.
- Autonomous acts – Statutes, collective agreements, and labour rulebooks of joint-stock companies registered for the activities of marinas, vessel chartering, and maritime transport.
- Professional studies and internal documents – Risk assessments, evacuation and rescue plans, and operational decisions of employers regarding occupational safety and fire protection.

2.3. Research Methods

A multi-methodological approach rooted in qualitative methods of scientific and professional analysis was applied in this paper. Due to the focus of the research subject on legal regulation and actual working conditions, the following methods were used: the normative (dogmatic) method, the content analysis method, the comparative method, the deduction method, the classification method, and the description method.

3. REGULATION OF RELATIONS

Occupational health and safety in facilities where nautical tourism activities are conducted—in accordance with the Constitution of the Republic of Croatia, universal principles of maritime safety law, and secondary sources of European Union (EU) law—are governed (regulated) by heteronomous and autonomous acts (general regulations). these involve different addressees, various procedures for enacting regulations, tiered levels of specialized content, spatial and temporal validity, and other nomotechnical marks. [10] [9] [7] [1] [11]

In heteronomous regulations governing occupational safety, there are no provisions directly addressing the rights, obligations, and responsibilities of labor subjects and workplaces specifically in nautical tourism activities at sea. To a certain extent, this is supplemented by the legal rules of general autonomous labor law acts enacted by the competent bodies of employers and associations, as social partners, in accordance with the law. [9] [2] [3]

As in other sectors, OHS issues and relations in nautical tourism are regulated by: the statutes of commercial companies (concessionaires on maritime domains) in marinas and other nautical tourism facilities, labor regulations, risk assessments, evacuation and rescue plans, decisions on child protection, and others. [3]

3. CONTENT OF REGULATIONS

The content of regulations governing occupational health and safety is based on the fact that these involve human rights and freedoms, the principle of prevention (according to basic, special, and recognized rules of occupational safety), and the employer's obligations in implementing occupational safety (training, information, and specifically the protection of workers performing jobs with special working conditions; protection of particularly vulnerable groups of workers and personal protective equipment; working environment and protection of work from pollution; fire protection, health care at work, and more). Rights, obligations, and the responsibility of workers and workers' OHS representatives, employer authorized persons, records, OHS experts, and numerous other issues and relations are specifically prescribed. [2] [3]

3.1. Content of General Autonomous Normative Acts

Employers in nautical tourism activities regulate subjects, procedures, measures, means, deadlines, and other OHS issues primarily through those acts and with the content as determined by law (though not always precisely and completely).

3.1.1. Statute - Constitutive Act of a Joint-Stock Company (d.d.)

The statute of a commercial company registering the activity, based on the right to a concession of a specific maritime domain, contains provisions on occupational health and safety in marinas and other facilities where the activity is conducted, alongside the legally required content. [8] [6] [5]

Crucial for the content of work is the definition of the company’s activities: marina activities, vessel rental, sea and coastal transport, organization and management of maritime safety, and others (repair of vessels, anchorages, moorings, dry marinas, etc.). The Management Board organizes tasks related to OHS.

3.1.2. Collective Agreement

The collective agreement is the most authoritative general act regarding working conditions at the employer level. In accordance with the Labor Act, it regulates: prohibition of discrimination, employment contracts, wages and compensations, working hours, breaks and leaves, bonuses, social peace, and the protection of life, health, and privacy of workers (maintenance of marinas and other facilities; rights of OHS representatives, responsibilities for the implementation of measures, etc.). It also "delegates" OHS relations to be autonomously regulated by other general normative acts. [4]

3.1.3. OHS in Other General Autonomous Normative Acts in Nautical Tourism

All "actions" in marinas constitute preparation for sea voyages for persons on vessels, where rules on maritime safety and the protection of human lives and the environment must be respected. This applies especially to skippers as commanders of yachts and boats (special training, licenses, etc.). Workplaces in facilities (marinas and others) are established by the regulations on work organization and systematization of workplaces (title, conditions, competencies, etc.).

Specific general acts regulate issues of work and protective clothing and footwear (purpose, type, durability, quantity). These include: jackets (winter, summer), protective shoes "with a protective cap," rubber boots, rain suits, work overalls, PVC cloaks/raincoats, safety helmets, gloves (leather, rubber, sun protection creams), ear protection, safety glasses, protective masks, safety belts for work at heights, and more, for each workplace or worker.

Fire protection regulations govern: workplaces and workers in charge of fire protection, methods of execution (rights and obligations), training methods, reporting in case of accidents, categorization of facilities by fire risk, fire protection services, persons with special authorities and responsibilities, control of measure implementation, maintenance of equipment and installations, records, and more.

A separate act refers to the evacuation and rescue plan in marinas and the list of facilities where sudden events may occur that threaten the life and health of persons present, conditions for preventing or mitigating the effects of sudden events, means of explosion, etc.

Risk Assessment is a study that the employer is obliged to have, regulating: facilities intended for work, employer representatives for protection, methods of performing tasks, representatives, OHS experts, occupational medicine, OHS committee, drafting procedure, tasks performed, analysis and assessment of risks at work and in workplaces, documentation, sources and types of danger, equipment, jobs with special working conditions, and other data.

The Occupational Safety Regulations are enacted by the Management Board and regulate: the organization and implementation of OHS, protection of special categories of workers, rights, obligations, and responsibilities of workers and employers, OHS activities, supervision, reports, documents, records, and other matters.

The Rules of Procedure of the Occupational Safety Committee regulate: composition, authorities, meetings, reports, the status of preventive measures to avoid work injuries and other harmful consequences, the work of occupational medicine doctors, coordinators, experts, professional training of workers, execution of conclusions, and more.

Employer decisions with general norms are internal regulations on the organization and implementation of occupational safety (e.g., implementation of work processes in marinas, placement of safety signs and general notices at specific locations—moorings, anchorages, cranes, berths, etc.—fire protection measures, evacuation, and rescue).

3.2. Content of Regulations Determines Jurisdiction and Enactment Procedure

Occupational health and safety is a "living," demanding, complex, and precise system of relations in every activity. In nautical tourism, regulation (jurisdiction, procedure, spatial and temporal validity) is necessary, especially regarding implementation and supervision (control of every legal norm).

4. CONCLUSION

The conducted research on the occupational health and safety system within the specific conditions of nautical tourism in the Republic of Croatia indicates the exceptional complexity of the legal regulation in this sector. Work processes taking place on the maritime domain (in marinas, anchorages, berths, and dry marinas) are subject to the constant influence of specific organizational, technical-technological, and natural factors, thereby requiring an integrated approach that connects labor law, occupational health and safety law, and maritime law.

The analysis of the normative framework has revealed a crucial legislative gap: direct heteronomous regulations (statutes and bylaws) do not contain provisions that directly address the rights, obligations, and specific risks of workplaces within nautical tourism activities at sea. Due to this lack of specialized state regulation, the focus of legal regulation is justifiedly shifted to autonomous law. Autonomous general acts of employers (concessionaires) play a crucial role in compensating for the shortcomings of the heteronomous framework.

Through a multi-tiered document analysis, a clear hierarchy and functional division within the autonomous regulation have been established:

- The Statute of a joint-stock company sets the constitutional-legal foundation within the company, defines economic activities (marina management, vessel chartering, transport), and authorizes the Management Board to organize occupational health and safety tasks.
- The Collective Agreement acts as the most authoritative source of working conditions at the employer level, guaranteeing the protection of workers' lives, health, and privacy, while simultaneously delegating narrower technical aspects to specialized acts.
- Labor Regulations, Risk Assessments, and Evacuation and Rescue Plans represent the operational level of protection. They precisely systematize workplaces (such as skippers), prescribe highly specific personal protective equipment (intended for work at heights, protection against the effects of the sea and weather conditions), and regulate strict fire protection measures.

Ultimately, the paper proves that the effectiveness of the occupational health and safety system in nautical tourism directly depends on the quality, precision, and up-to-dateness of autonomous acts. Only through the synergy of general legal principles of prevention and highly specific internal rules of employers can adequate protection of human lives, preservation of workers' health, maritime safety, and protection of the marine environment be ensured.

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Professional paper

RADIO COMMUNICATION SYSTEMS OF CIVIL PROTECTION IN THE REPUBLIC OF CROATIA

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Abstract: *Radiocommunication systems are crucial for the efficient functioning of civil protection. This paper explores the role, structure, and application of such systems in crisis situations such as natural disasters, technical-technological accidents, and other emergencies. The focus is on analysing technologies that enable fast and reliable information transfer among various services, including firefighters, emergency medical teams, police, and other emergency services. The paper also addresses implementation challenges such as interoperability between different systems, communication security, and adaptation to specific conditions. The aim is to demonstrate how radiocommunication systems represent a fundamental tool for coordination and rapid decision-making in crisis situations, while highlighting possibilities for further improvements in the future.*

Keywords: *civil protection, radiocommunications, interoperability, TETRA, management*

1. INTRODUCTION

Radio communication systems used in the civil protection services of the Republic of Croatia are among the most important tools for effective crisis management [1]. They enable end users to exchange information quickly, accurately and securely, and their purpose extends beyond internal service use, they also connect different services for coordination and management at all levels, which is essential for safety and efficiency.

Technological progress, including modern communication systems, wireless networks, application solutions, and IoT devices, has given services the ability to monitor and manage resources more easily and safely, as well as to adapt rapidly in the event of major disasters such as floods, earthquakes, fires, and man-made accidents. Despite these improvements, challenges remain in the areas of interoperability, reducing security risks, and providing adequate training for end users.

The geographical and demographic characteristics of Croatia, combining urban, rural, and remote areas, make the implementation of a quality radio communication system both technically demanding and economically costly. The system must support force coordination at tactical, operational, and strategic levels simultaneously.

This paper presents the radio communication systems of civil protection in Croatia, focusing on their technical characteristics, strengths, weaknesses, and opportunities for further development. It also addresses organisational aspects of radio communications in force management at the tactical, operational, and strategic levels.

The objective of this paper is to compare the TETRA, DMR, and conventional analogue radio communication systems currently used by Croatian civil protection services, evaluating them across the criteria of interoperability, network coverage, reliability, and cost-effectiveness. The paper adopts a descriptive and comparative technical review approach. Information was gathered from official Croatian regulatory documents (including the Civil Protection Act and the Ordinance on Radio Communication in Civil Protection), publicly available institutional sources, European Telecommunications Standards Institute (ETSI) standards documentation, and the professional operational experience of the authors, who serve in emergency medical services and the public fire brigade.

2. BASICS OF RADIO COMMUNICATION

Signal transmission in radio communications allows for fast, reliable, and wireless transmission of information over long distances. Various factors, such as frequency, signal strength, environmental conditions, and physical obstacles, can affect transmission quality, making careful planning essential. The basic principle relies on wireless transmission via radio frequencies, enabling instantaneous data exchange between field teams and operations centres [2].

2.1. Communication Working Principle

Signal transmission in radio communications is the process of sending information through electromagnetic waves. The process involves several key steps: (1) Modulation, information is added to the carrier wave by changing its characteristics (amplitude in Amplitude Modulation – AM, frequency in Frequency Modulation – FM); (2) Transmission, the modulated signal is radiated through an antenna; (3) Reception, the receiving antenna captures electromagnetic waves and converts them to electrical signals; (4) Demodulation, the signal is processed back into a form understandable to humans or devices.

Key technical concepts include: frequency (oscillations per second), antenna design and length (determines resonant frequency and efficiency), radio signal propagation (affected by terrain, weather, and obstacles), interoperability (ability of different systems to communicate), encryption (protection against unauthorised interception), Software-Defined Radio (SDR), and Internet of Things (IoT) [5].

Radio devices are classified by purpose into three categories: handheld (portable) devices, mobile devices (installed in vehicles, vessels, or aircraft), and stationary devices (installed in workplaces and operational centres). Figure 1 illustrates these categories.



Figure 1: Division of radio devices by purpose [2]

Two types of antennas are most commonly used in protection and rescue services:

Vertical antenna: radiates equally in all horizontal directions; its length is 1/2, 1/4, or 5/8 of the wavelength λ. Used on Very High Frequency (VHF) and Ultra High Frequency (UHF) bands (Figure 2).

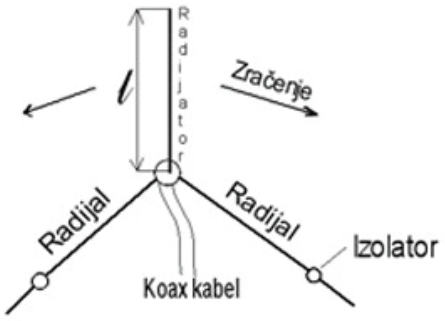


Figure 2: Vertical antenna [2]

Yagi antenna: a directional antenna consisting of a radiator (dipole), one or more directors that focus radiation in the desired direction, and a reflector that reduces radiation to the opposite side. The more elements, the stronger the signal (Figure 3).

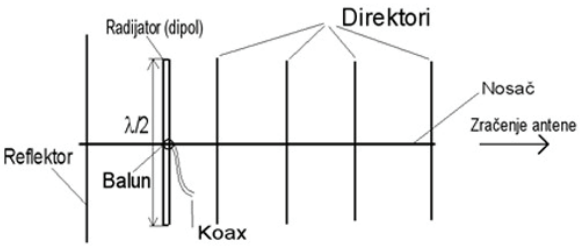


Figure 3: Yagi antenna [2]

Radio signal propagation is affected by terrain, atmospheric conditions, obstacles, and distance. The basis of radio communication is line of sight, the greater the unobstructed range, the better the quality of the radio link. Figure 4 illustrates the main sources of signal loss.

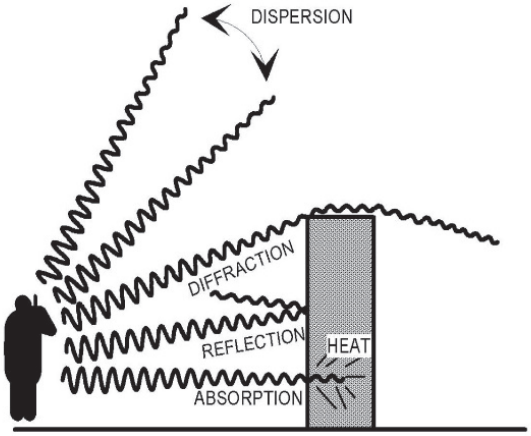


Figure 4: Signal losses [2]

2.2. Legal Framework for the Use of Radio Communications

In the Republic of Croatia, the use of radio systems in civil protection was regulated in 2017 through the Ordinance on the Method of Operation in Radio Communication Activities for the Needs of the Civil Protection System in Major Accidents and Disasters (Official Gazette, Narodne novine – NN, 53/2017) [6].

At the international level, the key document is "Radiocommunications in Emergency Situations," part of the General Radio Regulations established by the International Telecommunication Union (ITU). This framework ensures efficient, coordinated, and safe use of the radio frequency spectrum during emergency situations [7].

2.3. Radio Directory

Each service maintains its own radio directory, a document that defines universal call signs by which end users are identified in radio traffic. A properly defined directory allows the reader to determine from a call sign: the unit affiliation, type of device used, command level, and type of vehicle appearing on air [3]. Table 1 shows an example from the Public Professional Fire Department Osijek (JVP Osijek).

Table 1: Example of a radio directory, command structure of JVP Osijek [3]

Call Sign (Word)	Call Sign (No.)	Unit	Cmd. Level	Post
OSIJEK	200	2 - JVP	0	VOC JVP
OSIJEK	201	2 - JVP	0	Commander JVP
OSIJEK	202	2 - JVP	0	Deputy Commander JVP
OSIJEK	203	2 - JVP	0	Assistant Commander JVP

Call Sign (Word)	Call Sign (No.)	Unit	Cmd. Level	Post
OSIJEK	211	2 - JVP	1	Shift Commander 1
OSIJEK	212	2 - JVP	1	Shift Commander 2
OSIJEK	221	2 - JVP	2	Shift Leader 1

3. CIVIL PROTECTION RADIO COMMUNICATION SYSTEMS IN CROATIA

Civil protection services in Croatia use three main types of radio communication systems: TETRA (Terrestrial Trunked Radio), DMR (Digital Mobile Radio), and conventional analogue systems. TETRA is a professional digital trunked radio standard developed by the European Telecommunications Standards Institute (ETSI) [8], offering encrypted voice and data communication, group calling, and direct mode operation. The Croatian Ministry of the Interior has deployed TETRA with AVL (Automatic Vehicle Location) and DataQuery functionalities [9].

DMR is used primarily by firefighting units and other emergency services for its robustness and cost-effectiveness. Analogue systems remain in use in certain regions as backup when digital infrastructure is unavailable. Each system type is governed by the Civil Protection Act [10].

3.1. TETRA Network Organisation

The TETRA network is organised into hierarchical folder structures within which groups are created for specific services. Three modes of operation are supported: Wide Trunked Mode Operation (TMO) (through national/regional base stations), Local Trunked Mode Operation (TMO) (through county-level base stations), and Direct Mode Operation (DMO) (simplex operation for short-distance work).

The DINARA folder covers the entire Republic of Croatia (Figure 5). Groups within this folder are identified by a lowercase prefix letter: "d" for Civil Protection of the Ministry of the Interior (5 groups, suffix DINARA), "v" for Firefighting (5 groups, suffix ISKRA), "c" for Civil Protection of local government (5 groups, suffix CETINA), and "g" for the Croatian Mountain Rescue Service, HGSS (3 groups, suffix PLANINA) [4].



Figure 5: DINARA map, TETRA network coverage [4]

The hierarchical organisation of the TETRA network enables communication management at the tactical, operational, and strategic levels simultaneously, which is essential for coordinating large-scale civil protection operations.

4. CONCLUSION

The role of radio communications in modern society, and especially in civil protection systems, is extremely important for maintaining public safety, efficiency of action, and coordination of all subjects involved in crisis situations. This paper has provided a comprehensive overview of the basic concepts of radio communications, available technologies, legal regulations, and the specific communication systems used in the Republic of Croatia.

The analysis of TETRA, DMR, and analogue systems has highlighted their advantages in terms of reliability, security, and interoperability, as well as the disadvantages of each system. These systems enable seamless communication between different civil protection services, which is especially important in emergency situations when fast and accurate information is crucial for effective crisis management.

Future developments should focus on further integration with emerging technologies such as Low Earth Orbit (LEO) satellite communication [11], IoT-based disaster management platforms [12], specialized field command vehicles [13], and advanced encryption standards [14]. As demonstrated in a previous study on the civil protection system of the City of Zagreb, effective radiocommunication infrastructure is a prerequisite for successful coordination of all civil protection participants across command levels [15].

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Review article

THE ROLE OF ARTIFICIAL INTELLIGENCE IN DYNAMIC RISK ENVIRONMENTS

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Abstract: *Modern construction sites constitute highly complex and dynamic working environments in which the risk of fire occurrence and propagation is continuously present. Conventional, reactive fire protection systems are increasingly proving inadequate in addressing the challenges associated with rapid technological advancement and intensified urbanization. In this context, the integration of artificial intelligence (AI) and intelligent fire safety management systems is becoming a strategic imperative.*

This paper aims to analyze the potential of AI-driven intelligent systems in the field of fire safety management at construction sites—environments inherently characterized by dynamic conditions, instability, and elevated risk levels. Drawing on recent scientific literature and contemporary technological solutions, the study critically examines the advantages, limitations, and future research directions related to the application of AI in enhancing safety culture and improving fire prevention strategies in urban and industrial environments

Keywords: *Artificial intelligence, fire safety, construction site safely, fire detection, fire risk assessment, intelligent monitoring systems*

1. INTRODUCTION

Fire safety represents a fundamental aspect of modern urban living and construction, with essential importance for the protection of human lives, property, and the environment. Increased urbanization, technological advancement, and the emergence of complex and high-rise structures have significantly complicated the management of fire risks. In the past decade, as a result of economic growth and demographic changes, there has been a significant increase in the construction of large-scale public buildings [1,2,3]. This trend, particularly pronounced in rapidly urbanizing countries such as China (fig.1, fig. 2) not only raises architectural and engineering demands but also expands the range of potential fire scenarios.

Such complexity in architectural and engineering solutions raises numerous issues related to risk management, particularly in the domain of fire safety. Construction sites in densely populated areas do not allow improvisation: access to structures is limited, logistical corridors are narrow, and the evacuation of workers in case of fire is extremely difficult. Furthermore, modern façade systems, installation cavities, and the use of synthetic materials often increase the fire load and accelerate the rate of fire spread.

In this context, traditional fire protection systems, based on manual alarms, periodic technical inspections, and static evacuation protocols, are increasingly proving inadequate in addressing the challenges of the modern digital era.



Fig. 1 Construction area of public buildings in China (2013–2021) [2]

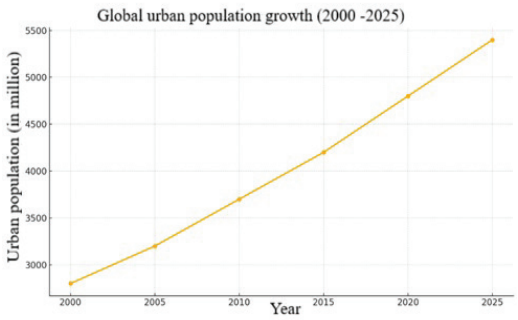


Fig. 2 Global urban population growth (2000–2025) [1]

2. CAUSES OF FIRE OCCURRENCE AND STAGES OF FIRE DEVELOPMENT

Construction sites, as open and dynamic environments, are characterized by an increased level of vulnerability to fire due to their specific organization, constant structural changes, and the use of diverse materials and machinery. Compared to completed structures, they represent high-risk settings in which multiple sources of potential hazards coexist, including flammable construction materials, unstable electrical installations, open sources of ignition, stored pressurized gases, as well as human factors resulting from non-compliance with safety protocols.

In particular, a frequent cause of fire is the use of temporary electrical installations that do not comply with regulations, faulty extension cables, ungrounded connections, and outdated or improvised equipment. Gas installations that are not properly sealed or inspected also pose a serious risk. The absence of early detection systems and inadequately positioned firefighting equipment further exacerbates the situation. These risks are significantly intensified in conditions of rapid urbanization, where the pace of construction exceeds the capacity of regulatory and supervisory institutions.

The application of traditional methods for safety assessment becomes inadequate in such contexts. Instead, the use of simulation tools is essential for modeling smoke propagation, evacuation dynamics, and intervention scenarios. Particular attention should be given to the early stages of design, where the integration of fire safety into the conceptual design can significantly reduce the need for costly and difficult-to-implement solutions in the later stages of construction. Of course, the increase in the physical scale of buildings is not the only challenge. Modern public buildings are characterized by complex configurations, multifunctional spaces, and intensive human occupancy, meaning that even the smallest fire can have serious, or even catastrophic, consequences. Fire safety

in such environments requires a new approach that goes beyond traditional, predominantly passive measures such as the installation of hydrant networks and fire extinguishers. In this context, there is a growing need for integrated systems for early detection, dynamic risk assessment, and efficient evacuation, particularly at construction sites where conditions and spatial organization change on a daily basis. Fire safety at construction sites does not depend solely on installed technical systems, but to a large extent also on the human factor. Errors made by workers, uncontrolled use of tools that generate sparks, disregard for safety procedures, and lack of familiarity with evacuation plans are among the most common causes of fire occurrence or escalation. Insufficient staff training, lack of regular training for handling flammable materials, as well as a weak safety culture, create conditions for increased risk.

Fires at construction sites can be classified according to their source, scale, and the construction phase in which they occur (tab.1) [4].

Table 1 Fire Risks by Construction Phase

Construction Phase	Observable Fire Risks	Risk Level
Preparatory works (site clearing, excavation, foundation works)	Combustible waste, unauthorized burning	Medium
Structural phase (reinforcement, concreting, scaffolding installation)	Sparks from cutting and welding, exposed cables	High
Installation and interior works (electrical, gas, ventilation)	Electrical faults, gas leakage	Very high
Finishing phase (decoration, painting, installation works)	Varnishes, solvents, paints – volatile substances	High
On-site storage of materials and machinery	Improper storage of flammable materials, overcrowded areas	Medium to high

3. THE ROLE OF ARTIFICIAL INTELLIGENCE IN ENHANCING FIRE SAFETY

When considering the application of artificial intelligence (AI) in the domain of fire safety, it cannot be treated as a single technology, but rather as an integrated ecosystem of interconnected solutions. This ecosystem encompasses a wide range of technologies, from automatic smoke and flame detection via thermal cameras and smart sensors, to advanced fire spread simulations aimed at predicting optimal evacuation scenarios. Such an approach requires a deep understanding of AI fundamentals, which is a prerequisite for its effective practical implementation.

One of the most significant contributions of artificial intelligence is its capability for early fire detection [5, 6]. By using systems based on computer vision and machine learning, it is possible to continuously analyze video footage in real time to promptly recognize smoke, flames, or atypical environmental changes. These systems enable significantly faster responses compared to traditional detection methods. Construction sites often involve high-risk activities such as welding, metal cutting, and handling of flammable substances. In this context, artificial intelligence enables automated monitoring of these activities and timely alerts in potentially dangerous situations. Specifically, this includes detecting sparks near flammable materials, identifying improper use of equipment, and recognizing deviations from prescribed safety protocols.

Additionally, by processing data from various sensors (temperature, humidity, gas concentration), AI systems allow early identification of conditions that indicate an increased fire risk. They can detect critical points on the construction site, warn of potential overheating of installations, and analyze complex combinations of risk factors. This analytical capability allows for the prediction of possible fire scenarios and the implementation of timely preventive measures, thereby significantly reducing the likelihood of unwanted incidents.

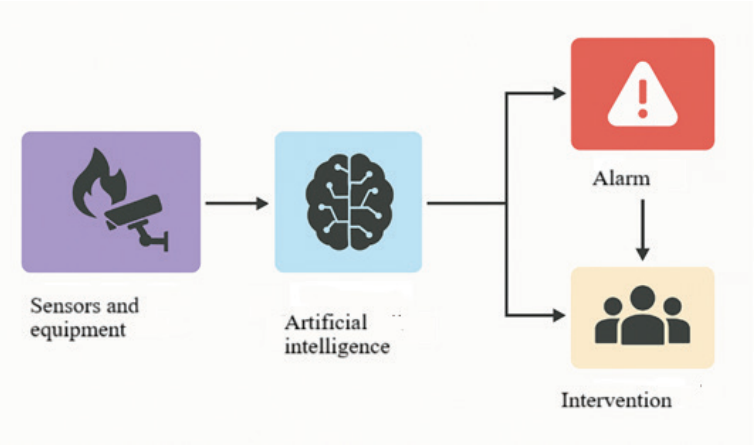


Fig. 3 Conceptual architecture of an intelligent fire safety system.

3.1 Development Trends of AI in Fire Safety

Current trends in artificial intelligence (AI) include integration with the *Internet of Things* (IoT), automated decision-making, explainable AI, and generative models capable of simulating complex scenarios. In fire safety, these technologies enable early detection, predictive analysis, real-time intervention planning, and evacuation management, all based on dynamic field data [7, 8, 9]

Importance of Predictive Simulation. Accurate simulation of potential fire events is essential for timely and effective risk management at construction sites. Modern approaches focus on early identification of potential fire sources and propagation pathways, rather than reacting after an incident occurs. Predictive mechanisms allow assessment of the impact on the environment, structural components, and evacuation routes before real hazards arise [10, 11].

Data Integration and Intelligent Algorithms. Predictive approaches rely on synthesizing data from sensor networks, historical incidents, meteorological information, and Building Information Modeling (BIM). Intelligent algorithms, based on machine learning and deep learning, generate simulations of fire development over space and time. Machine Learning Models include: Recurrent Neural Networks (RNN) and Long Short-Term Memory (LSTM) networks model temperature evolution, smoke density, CO_2 levels, and fire spread patterns.

Computational Fluid Dynamics (CFD) Simulations. CFD simulations complement algorithmic analysis, particularly for buildings with complex architecture. They model the movement of heat, smoke, and toxic gases, which is crucial for evaluating Available Safe Egress Time (ASET) versus Required Safe Egress Time (RSET).

Digital Twins for Real-Time Monitoring [12]. Digital twins—real-time digital replicas of physical spaces—are increasingly used for dynamic fire scenario monitoring. IoT sensor data feed into these models, allowing near real-time risk prediction. Example: If a thermal sensor detects a rapid temperature rise, the digital twin simulates potential fire spread and proposes optimal interventions immediately.

Incorporating Human Factors. Prediction extends beyond physical fire modeling to include human behavior analysis, such as the likelihood of errors, unsafe practices, or improper handling of tools and flammable materials. Integrating technical and behavioral parameters enables comprehensive risk profiling for specific work sites and activities.

Applications and Proactive Safety Management. Fire prediction scenario prediction serves as a foundation for proactive safety management. Insights from these models can be:

- Integrated into emergency response plans
- Used for personnel training
- Applied in the design of new structures with improved fire resilience

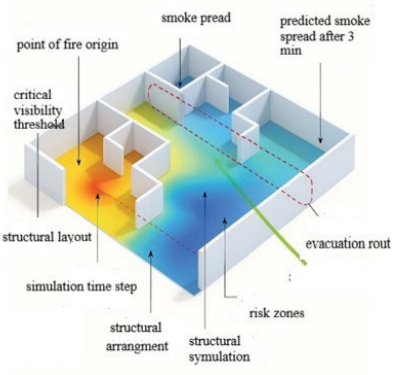


Fig. 4 CFD simulation for predicting the spread of smoke and heat in enclosed spaces

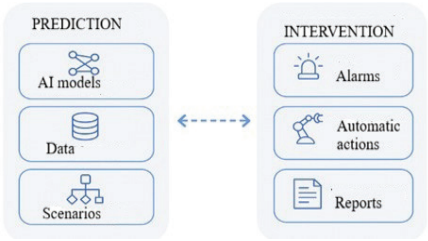


Fig. 5 Schematic representation of an intelligent system for fire prediction and intervention

4. ADAPTIVE AND INTELLIGENT FIRE SAFETY SYSTEMS

A key advantage of intelligent systems is their additivity and self-learning capability—the ability to adjust algorithms to new situations through feedback loops. This means the system not only learns from pre-trained models but also continuously updates itself in real time based on new field data, significantly enhancing its efficiency and relevance. These characteristics are particularly valuable in dynamic environments such as construction sites, where conditions change daily.

Intelligent prediction and intervention systems often include visualization modules, which display current risk levels, fire spread simulations, and recommended responses through 2D or 3D graphical interfaces. Such modules enable faster decision-making by safety managers and authorized engineers (see Fig. 5).

These systems rely on a network of integrated sensors—monitoring temperature, smoke, gases, flames, and movement—connected via an Internet of Things (IoT) infrastructure. When any sensor detects a deviation from safety parameters, an automated protocol is triggered, which may include:

- Local and central alarms
- Notifications via mobile applications
- Alerts to firefighting services
- Automatic activation of extinguishing systems (sprinklers, CO_2)
- Evacuation signals and guidance

A crucial feature of these systems is the use of edge computing, which processes data directly on the device without sending it to a central server, minimizing latency. Additionally, explainable AI (XAI-Explainable Artificial Intelligence) provides not only alerts but also information about why the alarm was triggered, supporting trust and effective interpretation.

In construction environments, these systems are designed to operate reliably under dusty, noisy, and frequently changing structural conditions. Alarms can be zone-specific, allowing particular areas of a site to be notified without unnecessarily disturbing other parts of the building.

5. PRACTICAL EXAMPLES OF AI AND IOT APPLICATIONS IN FIRE SAFETY

Japan – Intelligent Sensor Networks on High-Rise Construction Sites [3]

- Context: New building of the Ministry of Transport in Tokyo; high-risk construction site with welding, metal cutting, electrical installation, and painting activities.
- Solution: Intelligent thermo-sensors with machine learning algorithms to detect potential fires before they occur.
- Features:
  - Monitoring of temperature, dust, smoke, and flammable materials.
  - Predictive analysis based on historical data.
  - Integration with a mobile application for thermal maps and alarm notifications.
- Outcome: Early warning prevented a potential fire at a construction material storage site.

Hamburg, Germany – AI for Evacuation Scenario Analysis [13]

- Context: New underground transport hub with multiple corridors, lowered levels, and narrow passages.
- Solution: AI-based simulation system (reinforcement learning, agent-based modeling) to model real movements of individuals and groups under panic, low visibility, and smoke.
- Findings:
  - Main corridor would be non-functional under dense smoke.
  - Unfamiliar visitors tend to head to dead-end areas, causing confusion.
- Implemented Changes:
  - Additional evacuation stairs with independent ventilation.
  - Dynamic LED signage updated in real-time based on risk development.
  - Intelligent crowd control system using audio-visual cues to direct people safely.
- Results: Evacuation time reduced by 27%, safety rating improved from “high risk” to “acceptable level.”

USA – Automated Intervention System with IoT and AI [4].

- Context: High-rise mixed-use building in Austin, Texas; fire risk during vulnerable construction phases.

- Solution: IoT network combined with AI for early detection and automated intervention.
- Features:
  - Sensors for temperature, humidity, gas concentrations, smoke, and airflow.
  - Local processing via edge computing for faster decision-making.
  - Machine learning algorithms identify risk patterns preceding fire events.
  - Automated extinguishing systems, local alarms, notification of emergency services, and zone isolation barriers.
- Results: Prevented at least three major incidents (electrical panel overheating and two chemical handling issues) autonomously without human intervention.

China – IFETool: Deep Learning-Based Fire Prediction [14]

- Context: Development of the Intelligent Fire Engineering Tool (IFETool) with support from national research institutes and universities.
- Solution: Deep learning for automated fire safety assessment, predicting parameters such as temperature, smoke visibility, and CO concentration.
- Methodology:
  - Database of >10,000 CFD-simulated fire scenarios in atrium spaces with various geometries and combustible materials.
  - Neural network generates ASET (Available Safe Egress Time) profiles with up to 97% accuracy (NRMSE, SSIM).
  - BIM integration allows users to input architectural drawings and instantly receive simulations with safety design recommendations.
  - 3D visualization of smoke, temperature gradients, and critical zones.
- Application: Piloted in multifunctional buildings in Shanghai; early identification of critical design weaknesses.

6. CONCLUSION

The application of artificial intelligence on construction sites significantly enhances fire safety by enabling early detection, prediction, and automated intervention. Intelligent systems reduce risks to human lives and material assets while improving overall safety management on construction sites. Although there are limitations, such as high initial costs and the need for technical expertise, the benefits outweigh these challenges, indicating a clear future for AI as an integral part of modern construction.

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Professional paper

THE ROLE OF ARTIFICIAL INTELLIGENCE IN PLANNING TEMPORARY SHELTER IN THE TERRITORY OF THE CITY OF BIHAĆ

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Abstract: *The paper analyzes the application of artificial intelligence in planning temporary camps for populations affected by floods in the area of Bihać. It highlights that traditional methods, based on GIS analyses and expert assessments, are often slow and subjective, reducing their effectiveness in crisis situations. A model is proposed that combines GIS technologies, multi-criteria analysis, and machine learning algorithms to determine optimal locations for temporary camps. Key factors considered include geographic, infrastructural, safety, and demographic criteria, based on which a site suitability index is calculated. The expected output of the proposed framework is a conceptual suitability map that classifies locations according to their estimated suitability for temporary shelter establishment. The proposed methodology illustrates the potential of integrating artificial intelligence into emergency planning; however, the framework has not yet been implemented or empirically validated.*

Keywords: *Artificial Intelligence, camp, shelter, planning*

1. INTRODUCTION

Natural disasters represent one of the greatest risks to the population and infrastructure of urban areas. Among the most common natural disasters in Bosnia and Herzegovina are floods, which can cause significant material damage, displacement of the population, and the need to organize temporary accommodation for affected residents. The city of Bihać is particularly vulnerable to floods due to the Una river and its tributaries. During periods of heavy rainfall, the river overflows and floods urban and rural areas, creating the need to plan locations for temporary camps intended to accommodate the affected population. Traditional methods for planning camp locations are based on expert experience, GIS analyses, and surveys, but these methods have certain disadvantages such as outdated information, subjectivity, and difficulties in updating data. [1-3]. In addition, the increasing availability of spatial and environmental data has created new opportunities for the application of artificial intelligence in disaster risk assessment and emergency planning. Therefore, in recent years, artificial intelligence and machine learning have increasingly been used for planning locations of temporary camps. The aim of this paper is to analyze the role of artificial intelligence in planning temporary camps in the event

of floods in the territory of the city of Bihać and to present a model for selecting optimal locations. The paper also seeks to demonstrate the advantages of integrating artificial intelligence technologies into disaster risk management systems and to highlight their potential for improving the safety and protection of the population during natural disasters. This paper presents a conceptual framework for supporting the selection of temporary shelter locations in flood-prone areas by integrating Geographic Information Systems (GIS), multi-criteria decision analysis (MCDA), and machine learning techniques. Rather than reporting the results of an implemented decision-support system, the study proposes a methodological workflow that could be applied in future emergency planning. The framework has not yet been implemented or validated using real operational data; therefore, the presented suitability map should be interpreted as a conceptual illustration of the proposed methodology. Future research should focus on implementing the framework using real spatial datasets and evaluating its predictive performance under actual flood scenarios.

2. DISASTER MANAGEMENT AND TEMPORARY CAMPS

Disaster management represents an organized process of planning and implementing measures aimed at reducing the consequences of natural disasters such as floods, earthquakes, landslides, and fires. One of the most important tasks of the protection and rescue system is the organization of temporary accommodation for the affected population. The disaster management process is divided into four basic phases: prevention, preparedness, response, and recovery. Prevention includes measures aimed at reducing risks, preparedness involves evacuation plans and the organization of camps, response refers to rescue operations and population evacuation, while recovery includes infrastructure reconstruction and the rehabilitation of disaster consequences. When planning temporary camps, it is necessary to take a large number of factors into consideration. First of all, the camp location must be safe, meaning that it should not be situated in an area threatened by floods, landslides, or other hazards. Furthermore, it is very important for the camp to have good transportation connections in order to enable the arrival of rescue services and the delivery of food, water, medicine, and other supplies. In addition, the camp should be relatively close to populated areas so that residents can be evacuated more easily, while at the same time being sufficiently distant from the danger zone. Temporary camps must provide basic living conditions, including drinking water, food, sanitary facilities, electricity, healthcare, and security. It is also necessary to provide space for medical stations, storage facilities, and other supporting services. The size of the camp depends on the number of residents, and according to international standards, it is necessary to provide sufficient space for accommodation, roads, and common areas [5].



Figure 1: Example of an evacuation shelter

Traditional location selection is based on GIS analyses and expert assessment, but such an approach is often slow and subjective, making it difficult to process large amounts of data [4].

In recent years, modern methods such as multi-criteria analysis, optimization models, and artificial intelligence have increasingly been used for planning temporary camps. These methods enable the analysis of a large number of parameters and the identification of optimal locations within a relatively short period of time. Artificial intelligence techniques are particularly valuable because they can identify patterns from historical disaster data and support decision-making in future emergency situations and, based on available data, suggest the best possible locations for camps [6].

Planning temporary camps is of great importance for reducing the consequences of disasters, as a well-organized camp can significantly improve the living conditions of affected populations, reduce health risks, and enable more efficient coordination of aid.

Therefore, it is necessary to develop new planning methods that include the application of modern technologies such as GIS systems, remote sensing, databases, and artificial intelligence.

Based on all the above, it can be concluded that disaster management and temporary camp planning represent a complex multidisciplinary problem involving fields such as civil engineering, urban planning, geography, information technology, logistics, and crisis management.

Due to this complexity, the application of artificial intelligence represents a significant advancement in the planning and organization of temporary accommodation for the population in the event of natural disasters such as floods [9].

Modern AI systems enable dynamic monitoring and analysis of a large number of variables that influence the occurrence and development of floods, including meteorological data, hydrological parameters, and spatial terrain characteristics. This approach enables faster and more accurate risk assessment, which is of crucial importance for effective response in crisis situations.

The application of AI in crisis management includes various technologies such as machine learning, neural networks, big data analysis, and predictive modeling. These technologies enable the prediction of crisis development, identification of the most vulnerable areas, and optimization of resource allocation. In the case of floods, AI can analyze data related to rainfall, water levels, and terrain topography in order to predict possible flood scenarios.

The importance of artificial intelligence in crisis management is also reflected in its ability to learn from previous experiences. One of the most significant applications of artificial intelligence in flood management is predictive modeling.

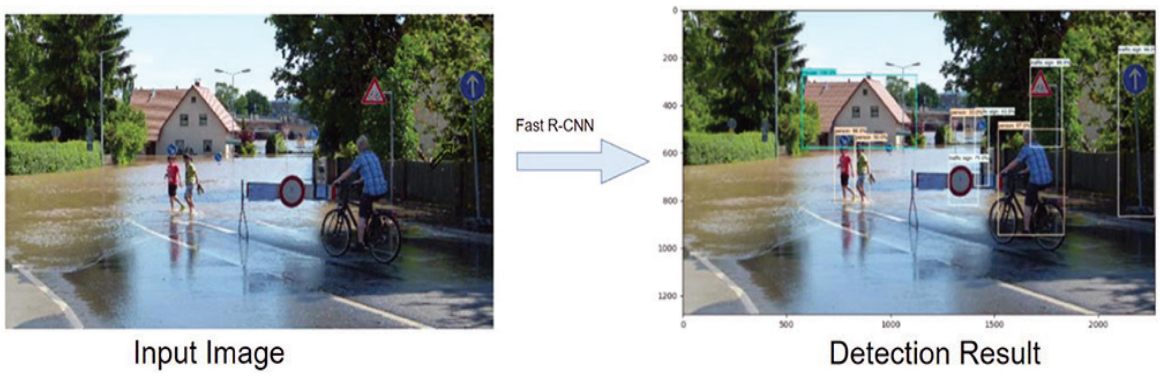


Figure 2: Example of AI-assisted hazard detection in flood-prone areas

Figure 2 shows an example of detecting potential hazards using artificial intelligence tools and photographic recordings of the observed location. By using machine learning algorithms, it is possible to analyze historical data related to hazards, rainfall, river water levels, and previous floods in order to predict future flood scenarios. These models can warn responsible authorities about potentially dangerous situations much earlier than traditional systems, providing valuable time for preparation and population evacuation.

AI is also used in early warning systems. By integrating water level sensors, meteorological stations, and satellite imagery, artificial intelligence can monitor environmental changes in real time and automatically generate warnings when an increased risk of flooding is detected. Such systems are particularly useful for the city of Bihać, where rapid changes in the water level of the Una River can lead to sudden floods.

3. APPLICATION OF THE MODEL TO THE CITY OF BIHAĆ

The city of Bihać has been affected by floods several times due to the Una River and its tributaries, which during periods of heavy rainfall can lead to the flooding of residential areas and infrastructure. In such situations, it is necessary to organize the evacuation of the population and provide temporary accommodation in safe zones.

Planning temporary camps in advance represents an important part of the protection and rescue system because it enables a faster and more efficient response in the event of a disaster. Instead of relying on improvised location selection, artificial intelligence models can be used to analyze spatial and infrastructural data and determine optimal locations for accommodating the population.

The artificial intelligence model for planning temporary camps in the area of Bihać is based on the analysis of multiple criteria that influence the suitability of a specific location for camp organization. These criteria are divided into geographical, infrastructural, safety, and demographic factors.

Geographical criteria include elevation above sea level, terrain slope, distance from the river, and soil stability. Locations at higher elevations and with lower terrain slopes are more suitable for camp organization because they have a lower flood risk and make it easier to establish temporary facilities.

Infrastructure criteria include access to main roads, proximity to hospitals, and the availability of water, electricity, and sewage systems, which enable the efficient functioning of the camp and easier delivery of aid. Accessibility to emergency shelters has also been identified as one of the most important criteria in previous optimization studies [7]. For the application of the model, spatial data are collected from GIS databases, satellite imagery, and topographic maps. Based on these data, thematic maps are created, such as flood zone maps, road networks, elevation maps, and population density maps, which are used for analysis and for determining the most suitable locations for organizing temporary camps. GIS-based multicriteria analysis has been widely applied for flood hazard zoning and site suitability assessment [8].



Figure 3: Example of a GIS map of the central area of the city of Bihać

Figure 3 shows an example of spatial data used in the artificial intelligence model for planning temporary camps. The map presents road networks, watercourses, urban zones, and green areas, which represent the basic criteria for analyzing location suitability.

In the model, these data are transformed into GIS layers, such as road, watercourse, and populated area layers, based on which artificial intelligence analyzes the area and determines the most suitable locations for organizing temporary camps.

Table 1: Example of criteria and weighting factors

Criterion	Weight factor
Distance from flood zone	0.25
Distance from roads	0.15
Distance from hospitals	0.15
Terrain slope	0.10
Elevation above sea level	0.10
Land use	0.10
Population density	0.10
Soil stability	0.05

Methodology of the Proposed Framework

The proposed framework consists of six sequential stages that integrate spatial analysis and machine learning techniques for identifying suitable locations for temporary shelters in the City of Bihać.

Stage 1 – Data collection. Spatial datasets are collected from publicly available GIS databases, topographic maps, satellite imagery, land-use databases, flood hazard maps, road network datasets, and demographic statistics. The selected datasets represent geographical, infrastructural, environmental, and socio-economic characteristics relevant for emergency shelter planning.

Stage 2 – Data preprocessing. Prior to analysis, all spatial datasets are projected into a common coordinate reference system and converted into raster layers with identical spatial resolution. Missing values are removed where possible, while spatial inconsistencies are corrected through GIS preprocessing procedures such as clipping, reprojection, and rasterization.

Stage 3 – Criterion standardization. Since the analysed criteria are expressed in different units, each variable is normalized to the interval between 0 and 1 using min-max normalization:

$$x' = (x - x_{min}) / (x_{max} - x_{min})$$

This procedure enables direct comparison between criteria and prevents variables with larger numerical ranges from dominating the suitability analysis.

Stage 4 – Weight determination. Each criterion is assigned a weighting coefficient according to its relative importance for temporary shelter planning. The weighting factors presented in Table 1 were derived from expert judgement supported by findings reported in previous literature on emergency shelter site selection. Future studies may determine these weights using structured decision-making approaches such as the Analytic Hierarchy Process (AHP).

Stage 5 – Machine learning framework. The normalized GIS layers represent the input variables of the proposed machine learning model. The conceptual framework considers several supervised classification algorithms, including Logistic Regression, Random Forest, Support Vector Machine (SVM), K-Nearest Neighbours (KNN), and Artificial Neural Networks [10]. The intended output consists of three suitability classes:

- Suitable
- Conditionally suitable
- Unsuitable

In the present study, these algorithms are proposed as alternative implementation options. No model training or comparative evaluation has been performed.

Stage 6 – Validation strategy. Since the framework has not yet been implemented using real-world datasets, no validation metrics are reported. Future implementation should divide the available data into training and testing subsets and evaluate model performance using Accuracy, Precision, Recall, F1-score, and Area Under the ROC Curve (AUC). Cross-validation procedures should also be employed to assess the robustness and generalizability of the predictive model.

4. RESULTS

The expected output of the proposed framework is a conceptual suitability map that classifies locations according to their estimated appropriateness for temporary shelter establishment. The map is intended to illustrate how the proposed methodology could support decision-makers during emergency planning rather than to present the results of a validated predictive model.

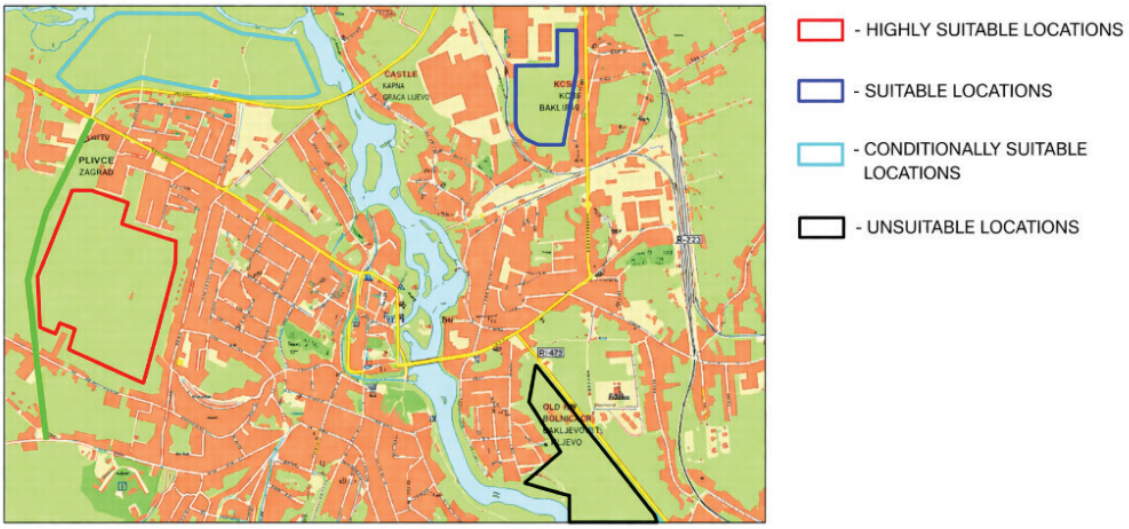


Figure 4: Location suitability map

Figure 4 illustrates a conceptual suitability map produced according to the proposed methodological framework. The map demonstrates how geographical, infrastructural, environmental, and demographic criteria can be integrated to classify locations into different suitability categories for temporary shelter planning. Areas identified as highly suitable represent locations that satisfy the majority of the selected criteria, including safe elevation, accessibility, and adequate spatial capacity. Locations classified as conditionally suitable may require additional infrastructural improvements before being considered for emergency use, while unsuitable locations correspond to areas exposed to flood hazards or other limiting factors. Since the proposed framework has not yet been implemented and validated using real operational data, the presented map should be regarded as a methodological illustration rather than as an experimentally verified prediction of shelter suitability.

5. CONCLUSION

This paper presented a conceptual framework for supporting the planning of temporary shelters in flood-prone areas through the integration of Geographic Information Systems (GIS), multi-criteria decision analysis (MCDA), and machine learning techniques. The proposed methodology aims to provide a structured approach for evaluating the suitability of potential shelter locations by considering geographical, infrastructural, environmental, and demographic criteria relevant to emergency management.

Unlike conventional approaches that primarily rely on expert judgement, the proposed framework demonstrates how spatial data and artificial intelligence techniques could be combined within a unified decision-support process. The conceptual workflow illustrates the potential for improving the consistency and transparency of site selection while facilitating the analysis of multiple decision criteria. However, the present study does not include the implementation, training, or validation of machine learning models using real-world datasets. Consequently, the suitability map presented in this paper should be interpreted as a conceptual representation of the proposed methodology rather than as an experimentally validated prediction.

The proposed framework provides a methodological basis for future research on AI-assisted emergency shelter planning in the City of Bihać and similar flood-prone areas. Future work should focus on implementing the proposed workflow using real spatial and environmental datasets, optimizing the weighting of decision criteria, training machine learning models, and evaluating their predictive performance through appropriate validation metrics such as Accuracy, Precision, Recall, F1-score, and Area Under the ROC Curve (AUC). Such validation is necessary before the proposed framework can be considered for operational use in disaster risk management and emergency response planning.

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Professional paper

APPLICATION OF ARTIFICIAL INTELLIGENCE IN AUTOMATED WOODEN PALLET

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Abstract: *Artificial intelligence (AI) is increasingly applied in automated manufacturing to improve productivity, product quality and occupational safety. This paper analyses the application of AI in automated wooden pallet production, with emphasis on machine safety, computer vision, predictive maintenance and process monitoring. The analysis shows that AI can reduce production downtime, improve defect detection and support safer working conditions by reducing operator exposure to hazardous operations. AI should be considered as a complement to existing machine safety systems such as optical barriers, emergency stop devices and PLC-based control. Furthermore, the integration of AI technologies enables continuous real-time analysis of production data, allowing faster decision-making, improved process optimization, and more efficient use of production resources. The findings indicate that combining artificial intelligence with modern automation technologies contributes to higher production reliability, enhanced operational efficiency, and the development of safer and more sustainable manufacturing systems.*

Keywords: *artificial intelligence; occupational safety; wooden pallet production; computer vision; predictive maintenance*

1. INTRODUCTION

The development of Industry 4.0 has introduced intelligent automation into manufacturing systems [1]. Modern pallet production combines mechanical, pneumatic, and electrical systems controlled by programmable logic controllers (PLCs), enabling high production rates, consistent product quality, and reduced manual labour. The integration of robotics, industrial sensors, and digital control systems has transformed traditional manufacturing processes, making them more efficient and reliable. However, despite the increasing level of automation, workers remain exposed to occupational hazards, including mechanical injuries, repetitive movements, wood dust, noise, vibration, and machine-related risks. Occupational safety therefore remains a key challenge in highly automated production environments. Although modern machinery is equipped with safety devices such as emergency stop buttons, optical safety barriers, protective guards, and interlocking systems, accidents may still occur due to human error, equipment malfunction, or unexpected

process deviations. Consequently, advanced technologies capable of continuously monitoring production processes and supporting preventive safety measures are increasingly important. Artificial intelligence (AI) can improve both manufacturing performance and workplace safety by analysing large amounts of production data in real time, detecting anomalies, supporting predictive maintenance, and enhancing quality inspection through computer vision [2]. These capabilities enable earlier identification of potential failures, reduce machine downtime, and minimise workers' exposure to hazardous operating conditions. Rather than replacing conventional safety systems, AI acts as an intelligent support tool that enhances decision-making and contributes to more reliable and efficient production processes. The aim of this paper is to analyse the application of artificial intelligence in automated wooden pallet production, with particular emphasis on occupational safety.

2. AUTOMATED WOODEN PALLET PRODUCTION

Automated wooden pallet production has become an important segment of the wood processing industry due to increasing market demands for higher productivity, standardised product quality, and improved occupational safety. Unlike conventional manufacturing, automated production systems integrate mechanical, pneumatic, electrical, and robotic technologies into a single process controlled by programmable logic controllers (PLCs). These systems enable continuous production with minimal operator intervention while maintaining high production accuracy and operational reliability. The production line analysed in this paper consists of a robotic manipulator, a pallet positioning station, pneumatic nailing units, conveyor systems, optical safety barriers, and a centralised control system. Each production stage is synchronised through a PLC, allowing continuous communication between sensors, actuators, and safety devices [3].

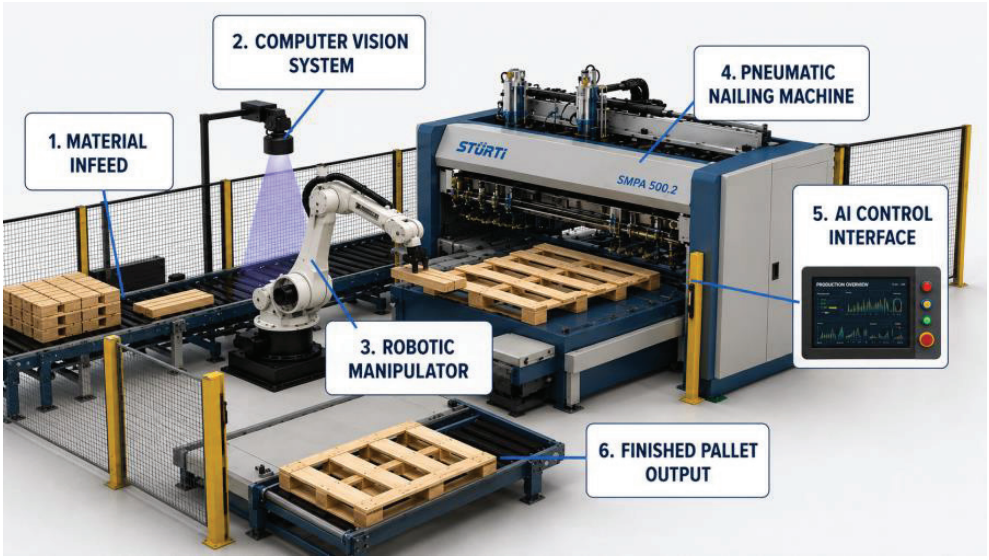


Figure 1. AI-supported automated wooden pallet production line with a robotic manipulator. AI-generated illustration

The production process begins by placing wooden boards onto the input conveyor. The robotic manipulator automatically transfers the boards to the production station, where the pallet structure is assembled according to predefined parameters. Before assembly, an AI-supported computer vision system identifies each wooden component and verifies its position. Incorrectly positioned

or damaged elements are automatically detected and removed from the production process, minimising defects and material waste. After successful inspection, the bridge mechanism positions the pneumatic nailing system above the pallet template. Nails are automatically supplied through pneumatic feeders, enabling rapid and continuous pallet assembly. Once the pallet is completed, the robotic manipulator transfers the finished product to the output conveyor while preparing the next production cycle. The entire process is continuously monitored by intelligent control algorithms that analyse production parameters, machine status, and sensor signals, enabling rapid identification of irregular operating conditions and reducing production downtime.

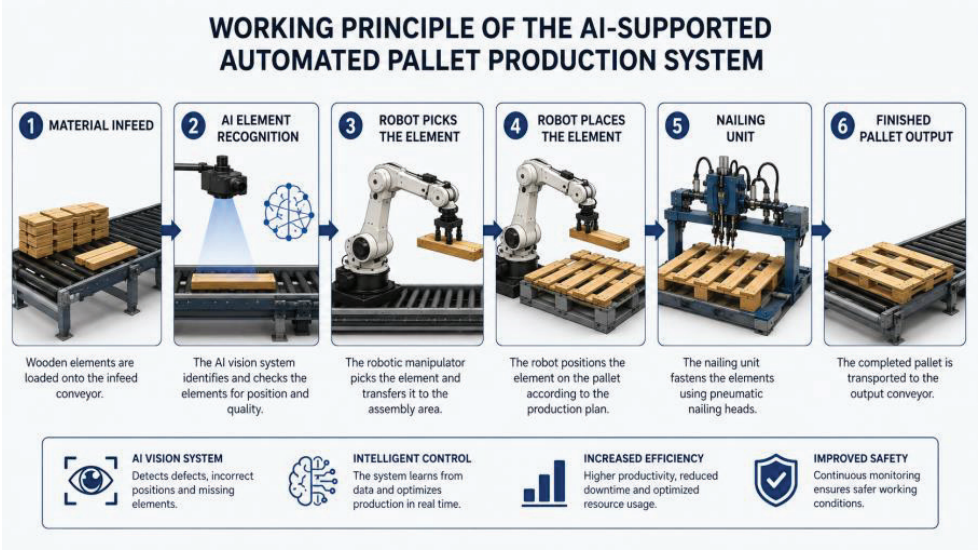


Figure 2. Working principle of the AI-supported automated pallet production system. AI-generated illustration

The integration of robotics with artificial intelligence enables autonomous process optimisation and significantly reduces the need for manual intervention. Nevertheless, human operators remain involved in material loading, supervision through the Human–Machine Interface (HMI), maintenance, and interventions following machine stoppages or process irregularities. During normal automatic operation, workers remain outside the protected machine area. Entry into hazardous zones is required primarily for maintenance or corrective intervention and should occur only after the machine has been stopped and appropriate safety procedures have been applied. Continuous monitoring of production parameters allows the system to respond quickly to operational deviations while improving production efficiency and workplace safety.

3. APPLICATION OF ARTIFICIAL INTELLIGENCE

Artificial intelligence has become a key enabling technology within Industry 4.0 by supporting intelligent automation, data analysis, and predictive decision-making. In automated wooden pallet production, AI can improve manufacturing efficiency while reducing occupational risks through continuous monitoring and intelligent process control. One of the most significant AI technologies applied in industrial manufacturing is computer vision [4]. Industrial cameras continuously monitor wooden components before assembly, allowing automatic detection of dimensional deviations, cracks, damaged boards, missing components, and incorrect positioning. Compared with manual inspection, computer vision provides faster and more consistent quality control while reducing reliance on subjective human judgement.



Figure 3. Computer vision system used for automatic detection and inspection of wooden components

Machine learning algorithms analyse operational data collected from sensors installed throughout the production line [5]. Parameters such as motor temperature, pneumatic pressure, vibration, cycle duration, and energy consumption are continuously evaluated to identify abnormal operating conditions. The system can learn from previous production cycles and predict potential failures before they occur, enabling predictive maintenance and reducing unexpected machine downtime [6]. Artificial intelligence can also improve production planning by optimising machine movements and synchronising individual production units. Intelligent algorithms can adjust production speed according to operating conditions, reducing unnecessary machine movements, minimising energy consumption, and increasing manufacturing efficiency.

The implementation of AI technologies contributes not only to improved productivity but also to higher product quality. Automated defect detection reduces the number of defective pallets reaching the final production stage, thereby lowering production costs and supporting consistent product quality [7].

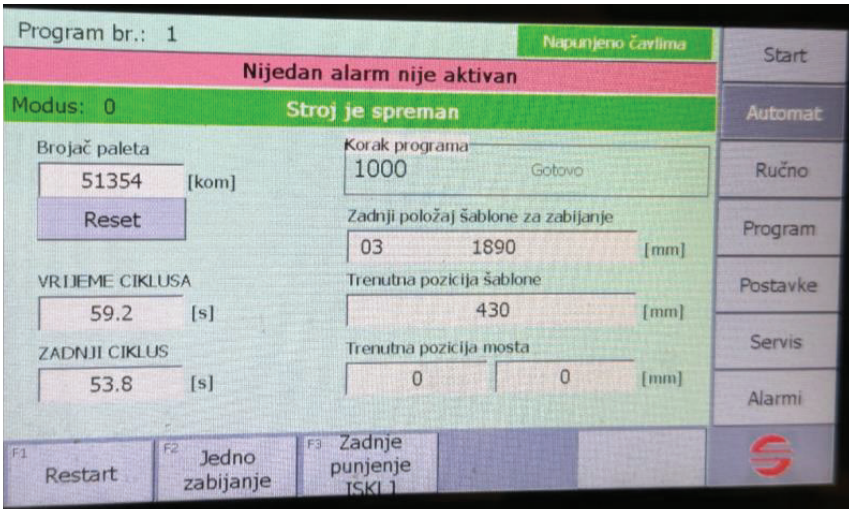


Figure 4. Human–Machine Interface (HMI) used for machine supervision.

4. OCCUPATIONAL SAFETY

Major hazards include moving bridge mechanisms, pneumatic nailing units, manual material handling, wood dust, noise, and mechanical vibration generated by motors, pneumatic equipment, and other moving machine components. In highly automated operation, direct worker exposure to vibration is generally limited; however, vibration remains relevant during machine operation, inspection, maintenance, and corrective interventions. Existing protection consists of optical safety barriers, emergency stop buttons, two-hand control, and PLC supervision. AI-based monitoring can further improve safety by detecting unsafe operator behaviour, identifying abnormal vibration patterns, and recognising hazardous situations before accidents occur [8-11].

Table 1. Occupational Hazards, AI Applications, and Safety Benefits in Automated Wooden Pallet Production

Production stage	Hazard	AI application	Safety benefit
Material loading	Manual handling	Computer vision	Posture monitoring
Automatic nailing	Mechanical injury	AI monitoring	Reduced operator exposure
Maintenance	Unexpected failure	Predictive maintenance	Lower accident risk

Table 2. Comparison between Conventional and AI-Supported Production

Parameter	Conventional Production	AI-Supported Production
Quality inspection	Manual visual inspection	Computer vision
Machine maintenance	Scheduled maintenance	Predictive maintenance
Operator supervision	Manual observation	Intelligent monitoring
Machine diagnostics	Fault detection after failure	Early anomaly detection
Production downtime	Higher	Lower
Human error	More frequent	Significantly reduced
Occupational safety	Conventional protection	Enhanced through AI monitoring

5. DISCUSSION

Artificial intelligence complements conventional machine safety rather than replacing it. Computer vision supports consistent inspection by detecting defective wooden elements before assembly, while machine learning can improve system reliability through predictive maintenance and early identification of abnormal operating conditions. Continuous analysis of data from sensors, cameras, and machine control systems supports earlier intervention, reducing unexpected failures, production downtime, and potential exposure to hazardous situations. AI-based monitoring also provides

operators with real-time information on machine status, production performance, and maintenance requirements, enabling faster corrective action. Successful implementation nevertheless requires investment, employee training, and continuous system maintenance. Operators must understand the function and limitations of AI-based monitoring and correctly interpret information displayed on the Human–Machine Interface (HMI). Appropriate training therefore remains essential for safe and effective use of AI technologies in the production process [12].

6. CONCLUSIONS

Artificial intelligence is an important technology supporting the transition towards intelligent manufacturing in the wood processing industry [13]. Its integration into automated wooden pallet production can improve manufacturing efficiency while enhancing occupational safety. Computer vision enables automatic defect detection and continuous quality control, whereas machine learning supports predictive maintenance through analysis of machine operating parameters, including vibration. Intelligent monitoring can support the early identification of hazardous situations and improve decision-making during production. Human operators nevertheless remain involved in material loading, supervision, maintenance, and corrective interventions, and conventional safety systems remain the primary protection against occupational hazards. AI therefore provides an additional safety layer through continuous monitoring, intelligent diagnostics, and preventive maintenance. Combining these technologies can contribute to lower accident probability, improved machine reliability, and increased production efficiency.

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Professional paper

GENERATIVE ENGINE OPTIMIZATION AS A NEW STRATEGY IN DIGITAL MARKETING

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Abstract: *This paper examines the evolution of Search Engine Optimization (SEO), the emergence of Answer Engine Optimization (AEO), and Generative Engine Optimization (GEO) as a new strategy in digital marketing. The empirical part of the study consists of a comparative analysis of two Occupational Safety Companies - Preventa and Centar zaštite na radu. The analysis includes AI visibility, brand mentions, cited pages, domain authority, and organic traffic indicators. The research findings indicate that traditional SEO metrics do not necessarily guarantee high visibility within generative artificial intelligence systems. In addition to domain authority and organic traffic, content quality, relevance, structure, and credibility were identified as significant factors influencing AI visibility. It can be concluded that GEO represents an important extension of existing digital marketing strategies and that its application will play an increasingly significant role in enhancing digital visibility and business competitiveness in the future.*

Keywords: *digital marketing, SEO, AEO, GEO, AI visibility*

1. INTRODUCTION

This paper analyzes digital content optimization strategies, with particular emphasis on Generative Engine Optimization (GEO) as a new paradigm in digital marketing amid the rapid advancement of artificial intelligence. This paper aims to present the development of optimization strategies, from traditional Search Engine Optimization (SEO), through Answer Engine Optimization (AEO), to Generative Engine Optimization (GEO), and examine the visibility of selected Croatian companies in generative AI systems using the Semrush tool.

The methods used in this paper include analysis and synthesis, descriptive method, comparative method, and case study method. In the research section, a comparative analysis of selected Croatian occupational safety companies was conducted using data collected through the Semrush

tool. The data sources included scientific and professional papers, relevant literature in the field of digital marketing, online sources, and data obtained through original research. The paper consists of five parts: introduction, literature review, analysis, discussion, and conclusion.

2. LITERATURE REVIEW

Digital marketing, as a new branch of marketing, emerged with the advent of the first search engines and was first mentioned in the 1990s. Although there are various definitions of digital marketing, it is most commonly defined as the marketing of products and services through the use of digital technologies to acquire and retain customers, promote brands, and increase sales. [1] Chaffey and Ellis-Chadwick define digital marketing as an approach to achieving marketing objectives through the use of digital media, data, and technology.[1] With the emergence of new media, technological advancements, and the rise of artificial intelligence, digital marketing continues to evolve in accordance with changing trends and user behavior.

In late 2022, the launch of OpenAI's ChatGPT attracted significant public attention due to its ability to generate human-like text in real time. For the first time, a broad range of users could ask an artificial intelligence system complex questions and receive meaningful, detailed, and contextually relevant responses. This development represented not only a technological innovation but also a new way of accessing information. Rather than browsing through conventional search results, users could communicate with the system in natural language and receive more precise, personalized responses tailored to their queries.[2] This type of interaction has also contributed to changes in user behavior, as users are increasingly moving away from analyzing lists of links and instead expecting direct, contextually relevant answers. In addition to ChatGPT, other tools such as Claude, Google Gemini, and Perplexity AI have emerged, further reinforcing the trend toward integrating generative artificial intelligence into information search processes. All of these tools share a common characteristic: they position generative artificial intelligence as an intermediary layer between users and information sources.[2]

As a consequence of these changes, SEO strategies are undergoing significant transformation. The focus is gradually shifting from keyword-based optimization and link building toward optimizing content for answer engines and generative systems (AEO and GEO) [3]. This shift has a significant impact on digital marketing and online content visibility, as information is increasingly being interpreted and delivered by AI systems rather than traditional search engines [4].

The foundation of AEO lies in understanding user intent. Unlike the traditional approach, which focuses on keyword-based content optimization, AEO involves creating content that is tailored to the actual questions and search patterns used by users in everyday communication. Key elements of AEO include creating clear and concise content structured around questions and answers, using structured data, and organizing information through headings, subheadings, lists, and bullet points. It also involves anticipating the different ways users may phrase similar queries and building content authority and credibility to ensure that search engines recognize the provided answers as reliable and relevant.[2]

Unlike traditional SEO, which primarily aims to generate clicks and achieve high rankings on search engine results pages, GEO focuses on ensuring that generative AI systems cite or reference a brand’s content in their responses. The content must be clear, self-contained, and authoritative enough for generative models to incorporate it into their responses with minimal modification.

Generative Engine Optimization (GEO) focuses on building a brand's digital authority and credibility so that generative AI systems recognize it as a relevant and trustworthy source of information. Unlike traditional SEO, GEO aims to increase a brand's visibility and the likelihood that it will be referenced by AI systems when generating responses to users.[2]

3. ANALYSIS OF THE GEO PERFORMANCE OF SELECTED CROATIAN OCCUPATIONAL SAFETY COMPANIES USING SEMRUSH

Semrush is a comprehensive platform for managing a brand's digital visibility, enabling the monitoring, analysis, and optimization of marketing activities across areas such as search engine optimization (SEO), AI-powered generative search, content marketing, and paid advertising. The platform is built on one of the industry's largest proprietary search databases, providing users with competitive insights and advanced analytical capabilities.[5]

To explore the role and importance of Generative Engine Optimization (GEO), the study examined the AI visibility of selected Croatian Occupational Safety Companies. The aim was to assess how prominently these brands are represented in generative AI systems and to identify differences in their visibility across AI-powered search. Two companies were selected for the analysis: *Preventa* and *Centar zaštite na radu*. The analysis was conducted using Semrush to assess brand visibility in generative AI systems and examine traditional SEO metrics. The study focused on AI Visibility, Mentions, Cited Pages, Authority Score, and Organic Traffic, enabling comparisons between the selected companies and an assessment of potential relationships between traditional SEO performance and AI visibility. AI Visibility measures how often a brand is represented or referenced in AI-generated responses [6], while Mentions reflects the frequency with which a brand appears across online platforms [7]. Cited Pages indicates the number of pages from a domain that generative AI systems use as sources, with a higher number suggesting greater content authority and credibility. A comparative analysis of Preventa and Centar zaštite na radu reveals differences in their SEO strength, organic visibility, and presence in generative search engines.

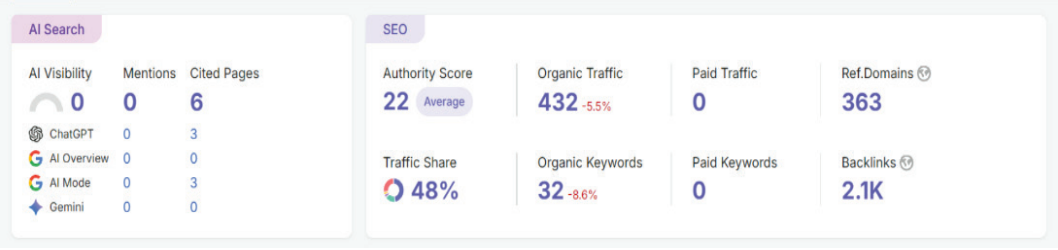


Figure 1. Indicators for Preventa Source: Semrush [2026-08-21]; authors' analysis/screenshot

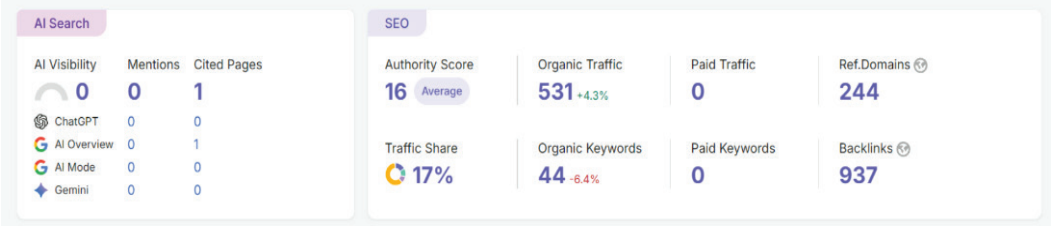


Figure 2. Indicators for Centar zaštite na radu Source: Semrush [2026-08-21]; authors' analysis/screenshot

In terms of AI Search, both companies have an AI Visibility Score of 0 and no recorded AI brand mentions. This indicates that, within the analyzed set of queries, neither Preventa nor Centar zaštite na radu appears as a recognizable brand in AI-generated responses. However, an important difference can be observed in the number of Cited Pages. Preventa has 6 Cited Pages, while Centar has only 1. Preventa's pages are cited in ChatGPT and Google AI Mode, whereas for Centar, one page is recorded in Google AI Overviews. In terms of traditional SEO metrics, Preventa achieves better results across most indicators related to domain authority. Its Authority Score is 22, compared with 16 for Centar. Preventa also has 363 referring domains and 2.1 thousand backlinks, while Centar has 244 referring domains and 937 backlinks. These results indicate that Preventa has a stronger, more developed backlink profile, as well as greater overall domain authority.

In contrast, Centar zaštite na radu performs better across several indicators of current organic search visibility. Its estimated organic traffic stands at 531, compared with 432 for Preventa, while Centar ranks for 44 organic keywords, compared with 32 for Preventa. Furthermore, Centar's organic traffic has increased by 4.3%, whereas Preventa has experienced a 5.5% decline. Despite these differences, both domains have recorded a decline in the number of organic keywords, with Preventa experiencing a decrease of 8.6% and Centar a decrease of 6.4%. Despite Centar's higher organic traffic, Preventa has a significantly higher Traffic Share, amounting to 48%, compared with 17% for Centar. This indicates that Preventa captures a substantially larger share of organic traffic within the analyzed competitive landscape. Therefore, it can be concluded that Centar currently performs slightly better in terms of absolute organic traffic, whereas Preventa holds a stronger relative market and SEO position. There are no differences between the two companies in terms of paid search performance. Both have 0 paid traffic and 0 paid keywords, indicating that their search visibility during the analyzed period is based primarily on organic search rather than paid advertising.

4. DISCUSSION

Overall, Preventa has a stronger SEO foundation and greater potential for developing a GEO strategy, while Centar zaštite na radu currently achieves somewhat better results in terms of organic traffic and the number of organic keywords. Particularly noteworthy is the fact that Preventa has six cited pages in AI Search, compared with only one for Centar. This indicates that Preventa's content is already present within the generative search ecosystem, but is not yet sufficiently optimized to result in direct brand mentions.

The analysis therefore confirms that traditional SEO strength alone does not guarantee high visibility in generative search engines. Domain authority, backlinks, and organic keywords provide an important foundation; however, success in generative search requires the further development of content that clearly addresses users' questions, demonstrates expertise, and enables AI systems to recognize the company as a relevant and trustworthy source. In this regard, Preventa is in a more favorable starting position, although both companies have considerable room to increase their AI visibility and transform their existing SEO presence into greater brand visibility and recognition in AI-generated responses.

In addition to the primary research, a second analysis was conducted to examine the relationship between traditional SEO performance and AI visibility among selected Croatian brands. By analyzing traditional SEO metrics alongside AI-related indicators, it was found that a higher level of domain authority, greater organic traffic, or a larger number of backlinks does not necessarily result in greater

AI visibility. For example, Podravka demonstrates relatively strong traditional SEO performance but does not record any AI visibility, whereas Jamnica, despite having lower values for certain SEO metrics, achieves one of the highest levels of AI visibility. These findings suggest that traditional SEO metrics alone are not sufficient for successfully positioning a brand within generative artificial intelligence systems.

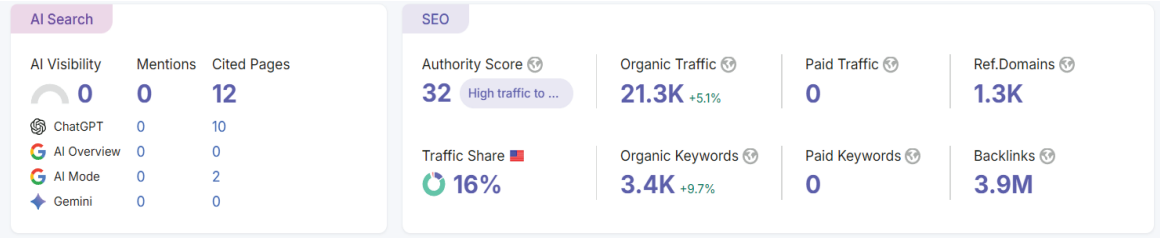


Figure 3. Indicators for Podravka Source: Semrush [2026-08-21]; authors' analysis/screenshot

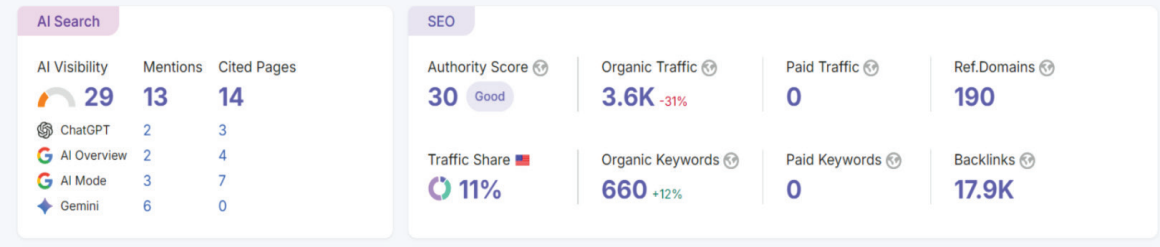


Figure 4. Indicators for Jamnica Source: Semrush [2026-08-21]; authors' analysis/screenshot

This result is particularly significant from a GEO perspective. An AI Visibility Score of 0 does not mean that generative systems do not find or use the companies' content at all. The Preventa example shows that AI systems already use certain Preventa pages as sources but do not explicitly mention or recommend the company itself. Preventa achieves a certain content presence in AI systems, but has not yet achieved brand visibility. Centar is in a weaker position, as its content has been recorded as a source only once. This indicates greater GEO potential for Preventa, but also highlights the need for further content optimization to increase the likelihood of the company being mentioned and recommended in AI-generated responses

5. CONCLUSION

The development of artificial intelligence has fundamentally changed the way people search for and find information online. With the growing use of generative AI systems such as ChatGPT, Gemini, and Perplexity, users are increasingly looking for quick, direct, and personalized answers rather than having to browse through numerous websites. These changes also have a significant impact on digital marketing, making it necessary for businesses to adapt their existing content optimization strategies. This paper examines the evolution of content optimization from traditional SEO, through AEO, to GEO as an emerging digital marketing strategy. The theoretical analysis shows that GEO does not replace SEO but rather builds upon it. While SEO aims to achieve higher rankings in search engine results, GEO focuses on increasing the likelihood that generative AI systems will recognize, use, and cite a brand's content. The findings show that traditional SEO metrics, such as domain authority and organic traffic, do not necessarily guarantee high visibility in generative AI systems.

A comparison of the selected Croatian Occupational Safety companies revealed that, in addition to traditional SEO metrics, AI visibility is significantly influenced by the quality and relevance of content, its structure, the credibility of its sources, and the extent to which it is optimized for generative AI systems. The findings confirm that digital visibility is no longer determined solely by search engine rankings, but also by the presence of brand content within AI-generated responses. For this reason, organizations should adapt their content and marketing strategies in a timely manner to keep pace with evolving search trends. It can be concluded that Generative Engine Optimization (GEO) will play an increasingly important role in digital marketing in the future. Businesses that recognize the importance of GEO early and adapt their content to the requirements of generative AI systems will be better positioned to increase their digital visibility, strengthen their competitive advantage, and achieve long-term business success. Further research in GEO must include companies from different industries and countries.

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INTEGRATED ORGANISATIONAL RESILIENCE–OCCUPATIONAL SAFETY FRAMEWORK: A MULTIDISCIPLINARY APPROACH, ASSESSMENT OPTIONS AND PILOT RESULTS (N = 88)

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Abstract: *The relationship between organisational resilience and occupational safety is typically examined separately in the literature whilst few frameworks are available that interpret human, organisational and safety factors within a unified model. The aim of this study is to present and conduct a preliminary empirical examination of an integrated organisational resilience–occupational safety assessment framework (IRAF). In the pilot study, we examined the dimensions of situational awareness and planning, safety–security integration, learning and reporting culture, and adaptation and development using a 20-item, four-dimensional questionnaire on a sample of 88 participants. The full scale demonstrated excellent reliability (Cronbach's α = 0.953). The results indicated moderate resilience maturity, whilst revealing a significant difference between the willingness to report errors (70.5%) and resilience awareness (33.0%). The research provides preliminary support for the idea that organisational learning, safety culture and resilience can be examined within a common assessment framework and lays the groundwork for validation research to be conducted on a larger sample.*

Keywords: *organisational resilience; occupational safety; safety–security integration; safety culture; resilience assessment*

1. INTRODUCTION

The cumulative crises of the past decade [1] have made it clear that the traditional occupational safety approach based on Safety-I logic is not sufficient on its own [2]. Due to the growing number of external stressors, modern organisations need not only to prevent accidents, but also to develop the ability to adapt to surprises and to understand the occupational safety climate [3]. This realisation gave rise to the distinct concept of organisational resilience, the practical measurement and assessment of which is enabled by, amongst others, the ICOR model and Hollnagel's Resilience Analysis

Grid (RAG) [4].These frameworks effectively describe and make measurable the organisational capabilities of resilience (foresight, monitoring, response, learning); at the same time, they pay relatively little attention to the human and cultural factors – safety culture, leadership behaviour, employee participation and psychological safety – that foster resilient functioning at the level of day-to-day work. In the literature, these concepts are typically examined in isolation, based on different theoretical backgrounds; consequently, there is no integrated model available that would treat them together with resilience and occupational safety outcomes within a shared explanatory framework. This gap is particularly striking in the Central European – and, within that, the Hungarian – context of small and medium-sized enterprises, where European occupational safety regulations and the domestic size structure create specific conditions.

Our study aims to bridge this gap, and its contribution to the research literature can be summarised in three points. First, it presents an integrated assessment framework that enables organisational resilience to be examined and compared across four theoretically grounded dimensions [4], [5]. Building on this, it provides a measurement table (Chapter 4) for the development of a measurement system for each dimension. Finally, it preliminarily substantiates the initial consistency of the items and dimensions with the results of a pilot data collection conducted on a Hungarian sample of 88 participants. The pilot measurement made it possible to identify and refine the direction of further research.

2. THE THEORETICAL BACKGROUND OF THE STUDY

To review the necessary theoretical background, let us first examine the primary sources.

(a) In the transition from Safety-I to Safety-II in safety science, the emphasis shifts from the elimination of errors to how an organisation remains operational under changing conditions. The RAG identifies four capabilities: monitoring, responding, learning and predicting [4], [5].

(b) The practical foundations of organisational resilience are also supported by research into High Reliability Organisations (HROs). According to the HRO approach, performance in the face of unexpected events is built on five mutually reinforcing processes of collective consciousness – sensitivity to errors and operational disruptions, rejection of oversimplification, sensitivity to operational performance, commitment to resilience, and respect for expertise. [6]

(c) Psychological safety refers to an organisational climate in which employees can report errors, share their concerns and draw attention to potential risks without fear of consequences.

(d) According to the transformational leadership model in management science, leaders' safety-oriented role modelling acts as a mediator of culture and participation [7].

To reduce the fragmentation of the holistic approach and provide a higher-level overview, the study examines how the findings of the four disciplines can be integrated into a common assessment framework.

During the pilot study, we developed an Integrated Resilience Assessment Framework (IRAF). The framework describes the functioning of organisational resilience along four interrelated dimensions: (1) situational awareness and planning, (2) safety–security integration, (3) learning and reporting

culture, and (4) adaptation and development. The model is based on the assumption that these dimensions collectively shape the organisation's adaptability and occupational safety performance.

The framework used in the research is based on the relationship between four dimensions:

- situational awareness and planning (D1) describe the organisation's capabilities for foresight, monitoring and preparedness;
- safety–security integration (D2) examines the extent to which occupational safety, physical security and business continuity considerations are reflected in a unified management decision-making system;
- the learning and reporting culture (D3) assesses the functioning of fault reporting, organisational learning and feedback mechanisms;
- adaptation and development (D4) measure the organisation's responses to change, its development practices and its long-term resilience-building capabilities.

The model assumes that these four dimensions collectively determine the organisation's resilience maturity and, through this, its occupational safety performance.

3. RESEARCH CHALLENGES, METHODOLOGY AND MEASUREMENT TOOLS

A difficulty encountered during the research was the challenge of conducting a comprehensive review of entire companies. The companies invited to participate in the study declined to take part, citing signs of an economic recession, ongoing workforce reductions, or the expected loss of working hours due to the time required to complete the questionnaire.

Consequently, the pilot sample consisted mainly of members of civil society organisations working on occupational safety and participants in adult training programmes on occupational safety. Due to the respondents' commitment to the topic and their diligence, all questionnaires were usable for the evaluation. This approach also had the advantage that it was not limited to assessing the internal culture of individual companies but provided an insight into the operations of Hungarian businesses.

The anonymous questionnaire was designed as a voluntary self-completion system, using a method that does not collect data traceable to specific individuals or email addresses, and which complies with GDPR guidelines. The first set of questions asked about the size of the company, the respondent's age, educational background, length of service at the company, job title, and their relationship to occupational safety. The second set of questions covered resilience-related topics. In the concluding questions, respondents were able to express their views on the survey, indicate the extent to which they would recommend that their line manager undertake the assessment, and estimate the likelihood of management participation.

The framework follows a two-stage empirical strategy: (i) a cross-sectoral pilot survey of 88 participants to assess the preliminary reliability and discriminatory power of the items and dimensions, and (ii) a planned, stratified main sample of 200–300 participants, which will be capable of testing the model and applying external occupational safety indicators (Lost Time Injury Frequency Rate, LTIFR; Mean Time To Recovery, MTTR).

4. EVALUATION OF PILOT RESULTS (N = 88)

The gender distribution of the pilot sample was 62.5% male and 37.5% female. Among the age groups, those aged 26–45 (51.1%) and 46–65 (40.9%) together accounted for over 90% of the sample. 95.5% of respondents hold a higher education qualification (BSc/BA: 46.6%, MSc/MA: 48.9%). The distribution by organisation size is bipolar: 27.3% are small enterprises (1–49 employees) and 38.6% are large enterprises (1,000+ employees); in terms of sectoral distribution, the manufacturing sector (n = 36) and services (n = 23) dominate. There were no missing Likert responses.

To measure organisational resilience, we used a self-report questionnaire consisting of 20 items rated on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree), covering four theoretically grounded dimensions: situational awareness and planning (D1, 6 items), safety-security integration (D2, 3 items), learning and reporting culture (D3, 4 items), and adaptation and development (D4, 7 items). The sample (N = 88) consisted of professionals working in the field of occupational safety and security within organisations in Hungary.

4.1 Overview of the research findings

Of the entire questionnaire, questions Q8–Q27 related to the topic of organisational resilience, the structural composition of which is shown in Table 1.

Table 1 Evaluation of research questions and responses

Item	Label	Dimension	Mean	SD	Top-2Box
Q8	Early risk recognition	D1 — Awareness & Planning	3,66	1,05	60,2%
Q9	Structured crisis decision-making	D1 — Awareness & Planning	3,75	0,95	64,8%
Q10	BCP review and update	D1 — Awareness & Planning	3,72	1,04	60,2%
Q11	Formal coordination mechanisms	D1 — Awareness & Planning	3,48	1,15	52,3%
Q12	Safety/Security in resilience decisions	D2 — Safety-Security integration	3,55	1,19	55,7%
Q13	Integrated risk management	D2 — Safety-Security integration	3,59	1,19	58,0%
Q14	Safety/security scenarios in BCP	D1 — Awareness & Planning	3,42	1,14	46,6%
Q15	Resilience review for new technology	D1 — Awareness & Planning	3,65	1,17	65,9%
Q16	Fearless error/near-miss reporting	D3 — Learning & reporting culture	3,91	1,10	70,5%
Q17	Employee suggestions implemented	D3 — Learning & reporting culture	3,77	1,05	65,9%
Q18	Safety on par with business goals	D2 — Safety-Security integration	3,23	1,08	39,8%
Q19	Employee resilience awareness	D3 — Learning & reporting culture	2,91	1,13	33,0%
Q20	Improved disruption prevention (3 yrs)	D4 — Adaptation & development	3,61	0,90	59,1%
Q21	Fast, structured incident response	D4 — Adaptation & development	3,70	1,02	60,2%
Q22	Lessons drive measurable change	D3 — Learning & reporting culture	3,58	1,06	58,0%
Q23	More resilient than 3 years ago	D4 — Adaptation & development	3,69	0,99	61,4%
Q24	Resilience in investment decisions	D4 — Adaptation & development	3,39	0,99	50,0%
Q25	Flexible procedures	D4 — Adaptation & development	3,45	1,06	52,3%
Q26	Crisis communication development	D4 — Adaptation & development	3,20	1,17	44,3%
Q27	Coordinated tech/process/HR develop.	D4 — Adaptation & development	3,34	1,06	43,2%

The table shows abbreviated versions of the research questions, the dimensions, the mean scores on the Likert scale, the standard deviation (SD) and the Top-2Box (the value of ratings 4–5 on the Likert scale). In the research, the questions were categorised into four dimensions:

- D1 — (Situational) Awareness & Planning,
- D2 — Safety-Security integration,
- D3 — Learning & reporting culture, and
- D4 — Adaptation & development.

It is worth highlighting the coexistence of the two extremes in the table. Whilst the Top-2Box figures for the reporting of fearless errors and near-miss situations (Q16) show a favourable 70.5%, the Top-2Box figure for employee resilience awareness (Q19) is only 33%. In the final questions of the questionnaire, which are not shown here, respondents were able to provide written explanations regarding their company's resilient operations and the auditability of organisational resilience. The limited number of text responses may suggest that resilience awareness at management level in Hungary may be even lower, and thus the safety net of organisational resilience may also be weaker.

Table 2: Evaluations along the dimensions of the research questions

Dimension / Scale	Items	Item mean	SD (total score)	SD / k	Top-2 Box	Cronbach's α	Reliability
D1 — Awareness & planning	6	3.61	5.23	0.87	58.3%	0.890	Very good
D2 — Safety-Security integration	3	3.45	2.84	0.95	51.1%	0.754	Good
D3 — Learning & reporting culture	4	3.54	3.39	0.85	56.8%	0.788	Good
D4 — Adaptation & development	7	3.49	5.77	0.82	52.9%	0.907	Excellent
Global resilience (all 20 items)	**20**	**3.53**	**15.63**	**0.78**	**55.1%**	**0.953**	**Excellent**

In the evaluation of the research by dimension, Table 2 contains the number of items per dimension, the mean, the standard deviation for the cumulative dimension score (SD-total score), the standard deviation (SD/k), the percentage of the two highest values on the Likert scale, the Cronbach's α value and the quality factor of the measurement results. The standardised deviation ranges from 0.82 to 0.95 across the four dimensions, indicating that there is a perceptible consensus among the respondents' views.

In addition to item-level descriptive statistics (mean, median, mode, standard deviation, response distribution), the proportion of positive ratings was presented using the Top-2 Box indicator (the combined proportion of responses 4 and 5). The internal consistency of the scales was measured using Cronbach's α [8]. The comparison of variance across dimensions was performed using the normalised SD/k index, which corresponds to the standard deviation of the respondents' mean scores [9].

4.2. Graphical evaluation of measurement results by item

Due to the apparent inconsistency observed in dimension D3, let us examine the distribution of individual items and their standard deviations.

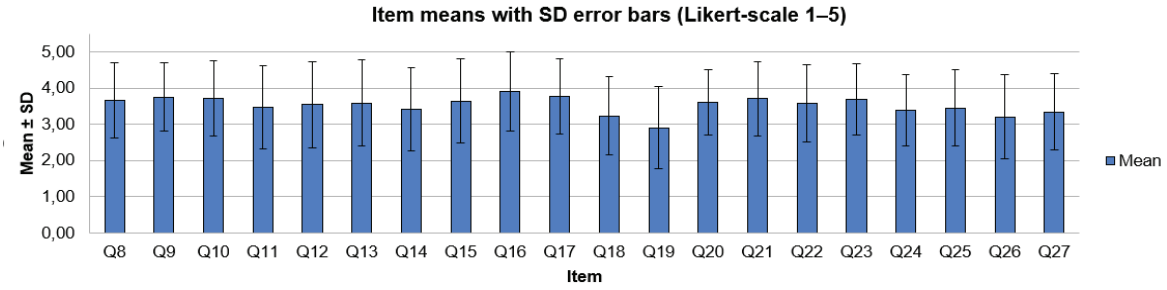


Figure 1 Mean scores for the 20 resilience items (1–5 Likert scale) based on a sample of 88 participants. The error bars indicate the standard deviation (SD). Taller bars indicate more favourable ratings, whilst wider error bars indicate more divided opinions

The absence of a ceiling effect in the diagram (no single item reaches an average score of 4.0) suggests that the scale has good discriminatory power and that the instrument is suitable for further statistical analyses (factor analysis, regression, group comparisons) — this enables the validation process of the questionnaire to continue The methodology is transferable and scalable; the questionnaire, the SD/k index, the error bar visualisation and the integrated item/dimension-level evaluation protocol constitute a reusable toolkit that can also be applied in other sectors for longitudinal and comparative studies.

4.3. Critical evaluation of the research dimensions

Given that the research is currently in its pilot phase, a critical self-assessment of the methodology was also important; therefore, we specifically examined the evaluation of the dimensions we proposed, a summary of which is as follows:

- D1 (Situational awareness and planning, α = 0.890) — Very good reliability. The six items show strong internal consistency, meaning that respondents consistently assess their organisation's foresight and planning capabilities.
- D2 (Safety-Security integration, α = 0.754) — Good reliability, but the lowest value of the four. The three items measure the concept collectively, but due to the small number of items, the α is more sensitive — the inclusion of an additional item with relevant content could stabilise the indicator.
- D3 (Learning and reporting culture, α = 0.788) — Good reliability. The four items form a coherent scale: error reporting, suggestions and the utilisation of lessons learnt move consistently together. A reliable dimension for measuring culture.
- D4 (Adaptation and development, α = 0.907) — Excellent reliability. The seven items (Q20–Q21 and Q23–Q27) measure the same latent variable with high consistency. This is the most robust dimension in the study — The seven items measure the construct of adaptation and development with high internal consistency.
- Global scale (all 20 items, α = 0.953) — Excellent. The full 20-item resilience scale measures with reliability consistent with, and indeed exceeding, the values reported in the literature. The α > 0.95 value indicates that a unified, well-defined variable underlies the measurement.

4.4. Top-2 Box analysis of the research data

- Based on the Top-2 Box results, the situational awareness and planning (D1) dimension received the most favourable rating (58.3%). This result points to the relative organisational maturity of risk perception and continuity planning capabilities; however, the 41.7% proportion of non-positive responses indicates the presence of significant room for improvement.
- Safety–Security integration (D2) achieved the lowest positive score (51.1%), which suggests limited organisational integration of occupational safety and security functions. The high standard deviation observed alongside adequate reliability (Cronbach's α = 0.754) indicates significant respondent divergence, so this area can be considered one of the most important priorities for resilience development.
- The positive score of 56.8% for the learning and reporting culture (D3) indicates moderate organisational maturity. The aggregate result presents a favourable picture; however, item-level analysis reveals further development needs in the areas of open error reporting and organisational learning.
- The positive value of 52.9% for the Adaptation and Development (D4) dimension indicates moderate organisational performance, whilst the high internal reliability (Cronbach's α = 0.907) preliminarily supports the strong coherence of the construct. The results point to further potential for development in the areas of organisational adaptation and resilience development.
- The Top-2 Box value of 55.1% calculated for the entire scale indicates moderate resilience maturity. According to the results, organisations possess the foundations for resilient operation; however, further development is required in the areas of safety–security integration and organisational learning to achieve highly reliable operation.

5. CONCLUSION

The results revealed the resilience maturity profiles of the organisations studied and identified the key areas for improvement. Of particular note is the lower score and greater variation in Safety–Security integration (D2), which points to significant differences in maturity between organisations. Particularly noteworthy is the discrepancy observed within the learning and reporting culture dimension: whilst the positive assessment of fear-free fault reporting and near-miss reporting was high (Q16 Top-2 Box = 70.5%), employee resilience awareness showed a significantly lower value (Q19 Top-2 Box = 33.0%). This may suggest that organisational mechanisms supporting the reporting of errors and incidents are already in place in many cases, whilst the concept of resilience and its organisational significance have not yet been integrated to a similar extent into employees' mindset. The result highlights that developing resilience is not merely a technical and organisational issue, but also a challenge of awareness and culture.

The findings on the culture of learning and reporting (D3) thus provide preliminary support for the view that error reporting and organisational learning mechanisms are measurable and developable resilience capabilities. The research contributes both to the theoretical development of organisational resilience and to the creation of an internationally applicable resilience assessment framework; however, further validation of the model and testing on a larger sample are required.

Study limitations. This pilot study has several limitations that should be considered when interpreting the findings. The sample was based on convenience sampling and consisted primarily of occupational safety professionals involved in civil-society organisations and adult-training programmes rather than employees drawn directly from the organisations originally targeted for the study. Consequently, the findings cannot be considered representative of Hungarian organisations as a whole. Nevertheless, this sampling strategy was appropriate for evaluating the preliminary reliability and internal consistency of the proposed measurement framework. The planned second-stage study will employ a substantially larger (200–300 participant), stratified organisational sample to examine the external validity and generalisability of the framework.

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Original scientific paper

WILDLIFE-VEHICLE COLLISIONS ON ROADS OF PLITVICE LAKES NATIONAL PARK

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Abstract: *This study examines wildlife-vehicle collisions (daily and annual dynamics) in Plitvice Lakes National Park during 2017 and 2018. A total of 62 incidents were recorded, with roe deer (Capreolus capreolus) accounting for 68% and wild boar (Sus scrofa) for 8%, while large carnivores—wolf (Canis lupus), brown bear (Ursus arctos), and lynx (Lynx lynx)—represented 6%. Collision data were analysed using GIS software (ArcMap 10.5.1) and the Kernel Density Estimation (KDE) tool. Two analyses, based on biomass and conservation status, identified five probability categories (A–E), ranging from low to very high collision risk, corresponding to "hot spot" locations. For each category, mitigation measures were proposed to reduce wildlife mortality and traffic-related damage. The applied methods can support future monitoring and improvement of mitigation strategies both in Plitvice Lakes National Park and other areas.*

Keywords: *wildlife-vehicle collision, Plitvice Lakes National Park, Kernel Density Estimation, biomass, conservation status*

1. INTRODUCTION

Plitvice Lakes National Park is the oldest and largest national park in Croatia. It was declared a protected area in 1949 and covers an area of 29,630.77 ha [1]. Roads crossing protected areas frequently create conflicts between transportation infrastructure and wildlife conservation. Wildlife–vehicle collisions (WVCs) are among the most visible consequences of habitat fragmentation and increasing traffic intensity. Apart from causing direct mortality of wildlife, collisions generate substantial economic losses and represent a risk to human safety. Plitvice Lakes National Park is visited by a large number of visitors every year and is intersected by major state roads connecting

northern and southern Croatia. Seasonal migration of wildlife, daily movements related to feeding and reproduction, and increasing tourist traffic create favourable conditions for collisions. Similar studies conducted across Europe have demonstrated that ungulates, particularly roe deer, are the most frequently affected species [2, 4, 7, 15]. The objective of this study was to analyse the annual and daily dynamics of wildlife–vehicle collisions in Plitvice Lakes National Park, identify collision hot spots using GIS methods and propose mitigation measures for reducing collision frequency and associated damages.

2. STUDY AREA

Plitvice Lakes National Park covers 29,630.77 ha in mountainous Croatia between the Mala Kapela and Lička Plješivica mountain ranges. Forests dominate the landscape, covering approximately 80% of the park area, while grasslands and meadows account for around 15% [1]. Plitvice Lakes National Park supports exceptional biodiversity, including more than 50 mammal species. Large mammals include roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), wild boar (*Sus scrofa*), brown bear (*Ursus arctos*), wolf (*Canis lupus*) and lynx (*Lynx lynx*). The coexistence of large herbivores and predators makes the area ecologically important but also increases the likelihood of road crossings. Plitvice Lakes National Park extends from 417 meters above sea level at the Korana River to 1,280 meters above sea level at Seliški Vrh, the highest peak of the Mala Kapela mountain range. Approximately 90.6% of the park lies within Lika-Senj County, while 9.4% belongs to Karlovac County [1]. Despite its protected status, the park contains 20 settlements with a resident population of 1,411 inhabitants, making it the most populated national park in Croatia [1]. Human settlements and transportation infrastructure occupy approximately 3% of the total park area, but their influence on wildlife movement and habitat connectivity is considerable. Approximately 64 km of state roads pass through the park. Traffic intensity increases substantially during the tourist season, especially along road D1, which serves as one of Croatia's most important north–south transportation corridors. In addition to state roads, the park contains nearly 160 km of forest roads and a similar length of paved roads. The main state roads crossing the protected area are D1 (15 km), D429 (14 km), D42 (12 km) and D52 (23 km). These roads intersect important wildlife habitats and migration routes, increasing the probability of wildlife–vehicle collisions. Traffic volume on the D1 road rises dramatically during summer due to tourism, with visitor numbers reaching several hundred thousand per month, creating additional pressure on wildlife populations and movement patterns. Previous studies have identified roe deer as the species most frequently involved in wildlife–vehicle collisions in Croatia [4, 7, 15], while the presence of large carnivores and other protected species further increases the conservation significance of road mortality within the park.

3. MATERIALS AND METHODS

Collision data were obtained from the Korenica Police Station and the Ranger Service of Plitvice Lakes National Park. Records covered the period from January 2017 to December 2018. For each collision, information on species, location, date and time was collected. A total of 62 wildlife–vehicle collisions were analysed. In addition to collision records, data on compensation payments for vehicle damage caused by wildlife collisions between 2014 and 2018 were obtained from the Plitvice Lakes National Park administration. During this period, insurance claims related to wildlife–vehicle collisions exceeded €80,000, highlighting the economic significance of the problem. Locations were

digitised using ArcMap 10.5.1 and displayed on topographic maps. Spatial analyses were conducted using Kernel Density Estimation (KDE), a commonly applied method for identifying spatial clusters and accident hot spots. Kernel Density Estimation is widely used in spatial ecology and road ecology studies to identify areas with elevated concentrations of events and has previously been applied to wildlife–vehicle collision analyses [9], traffic accident studies [7] and population density assessments [10]. In this study, a Gaussian kernel function was applied to estimate collision density and identify collision hot spots within the road network. A search radius of 400 m was selected to improve visualisation of collision clusters and account for the surrounding habitat used by wildlife near roads. Similar approaches have been recommended for wildlife collision studies using KDE methods [12]. Two weighting approaches were used. The first approach classified species according to biomass, assigning greater weight to large-bodied species capable of causing higher material damage and greater safety risks. Species with high body mass, including brown bear, red deer and wild boar, were assigned the highest weighting values because collisions involving these species may result in severe vehicle damage and increased risk of human injury. Intermediate values were assigned to roe deer, wolf and lynx, while smaller species such as fox, badger, hare and western capercaillie received lower weighting values. The second approach considered conservation status, giving higher values to protected and strictly protected species. Common game species (roe deer, red deer, wild boar, hare, fox and badger) received lower conservation scores, whereas strictly protected species such as wolf, lynx, brown bear and western capercaillie received higher scores. This approach allowed the identification of collision hot spots not only from a traffic safety perspective but also from a biodiversity conservation standpoint. The resulting KDE surfaces were classified into five categories: low, moderate, medium, high and very high collision probability. These categories enabled identification of priority areas for management intervention. The five probability classes were subsequently used to evaluate road sections according to collision frequency and risk level. Areas classified as high and very high probability were considered collision hot spots and were identified as priority locations for mitigation measures aimed at reducing wildlife mortality and improving road safety.

4. RESULTS AND DISCUSSION

Roe deer were by far the most frequently affected species, accounting for 68% of all recorded collisions. Wild boar represented 8% of collisions, while red deer accounted for 3%. Large carnivores, including wolf, lynx and brown bear, together represented 6% of cases. These findings are consistent with previous studies conducted in Croatia and elsewhere in Europe [2,7,8]. The predominance of roe deer in collision records reflects both their high population density and behavioural characteristics. Roe deer are widely distributed throughout the Plitvice Lakes National Park and frequently cross roads while moving between feeding and sheltering habitats. Similar proportions of roe deer involvement have been reported in studies from Croatia, Slovenia and Lithuania, where this species represents the majority of recorded wildlife–vehicle collisions [2,5,7]. Annual dynamics revealed pronounced peaks in January, May and August. Increased collision frequency during spring is associated with higher wildlife activity, territorial movements and dispersal behaviour. The elevated number of collisions recorded in January may be related to reduced driver visibility caused by adverse weather conditions, shorter daylight periods and the increased use of roads by wildlife searching for food resources during winter. The spring peak corresponds with increased animal mobility associated with reproductive activities and territory establishment [5, 13]. The August peak differs from many other Croatian studies and is most likely linked to intensive tourist traffic within the park. This finding highlights the importance of considering tourism-related

traffic pressure in protected areas. Unlike most studies conducted on Croatian roads, where autumn collision peaks are frequently observed, the pattern recorded in Plitvice Lakes National Park reflects the specific characteristics of a protected area exposed to intensive seasonal tourism. During summer, visitor numbers increase substantially, resulting in significantly higher traffic volumes on roads crossing wildlife habitats. Daily dynamics showed the highest collision frequency during early morning and evening hours. Similar patterns have been reported elsewhere in Europe [5]. Reduced visibility combined with increased wildlife movement during crepuscular periods likely explains this pattern. More than half of all collisions occurred during periods of dawn and dusk, when many mammal species exhibit peak activity levels. During these periods drivers have reduced reaction times due to lower visibility, while animals are more likely to cross roads during feeding and movement activities. These findings support previous observations reported by Pokorny [5] and other authors studying wildlife–vehicle collisions in Europe [2, 7]. Spatial analyses identified several collision hot spots. When biomass was used as the weighting criterion, four major high-risk locations were identified. The highest-density clusters were concentrated along sections of the D1 and D429 state roads, particularly in areas where forest habitats directly border road infrastructure. Several hot spots were located near tourist facilities, accommodation areas and visitor entrances, indicating a strong interaction between wildlife movement patterns and human activities. When conservation status was considered, larger sections of roads D1 and D429 were classified as high-risk because of the presence of protected species. This approach produced a broader distribution of high-risk areas because collisions involving strictly protected species such as brown bear, wolf and lynx received greater weighting values. Consequently, some road sections with relatively low collision frequency were nevertheless classified as conservation priorities due to the occurrence of species of high ecological importance. The increase in wildlife–vehicle collisions during August coincides with the peak tourist season and the highest number of visitors to Plitvice Lakes National Park. Most collisions were recorded near visitor parking areas and park entrances, suggesting that increased traffic intensity, combined with heightened roe deer activity during the breeding season, represents a key factor influencing summer collision rates. A comparison between monthly visitor numbers and collision frequency revealed a similar seasonal trend, with both variables reaching maximum values during August. Although a direct causal relationship cannot be confirmed from the available data, the observed pattern suggests that increased traffic intensity associated with tourism contributes substantially to collision occurrence. Similar relationships between traffic volume and wildlife mortality have been reported in previous studies [8, 9, 13]. These locations combine high traffic intensity with wildlife movement corridors. The concentration of collisions in these areas suggests that anthropogenic disturbance and increased vehicle numbers play an important role in collision occurrence. The spatial coincidence of collision hot spots and areas of intensive visitor use emphasises the need to integrate wildlife conservation and traffic management within protected areas. Such locations should be prioritised for future mitigation measures, including warning systems, traffic calming measures and enhanced driver awareness campaigns [3, 6, 14] The KDE approach proved effective for identifying critical road sections and visualising collision risk. Similar methods have been successfully applied in wildlife collision studies worldwide and provide valuable support for management decision-making [9, 10, 11, 12]. By incorporating both biomass and conservation status into the analysis, the method provided a more comprehensive assessment of collision impacts than simple collision counts alone. This approach enables managers to identify areas important both from a road-safety perspective and from the standpoint of biodiversity conservation, thereby improving the prioritisation of mitigation measures within the National Park [9, 11, 12].

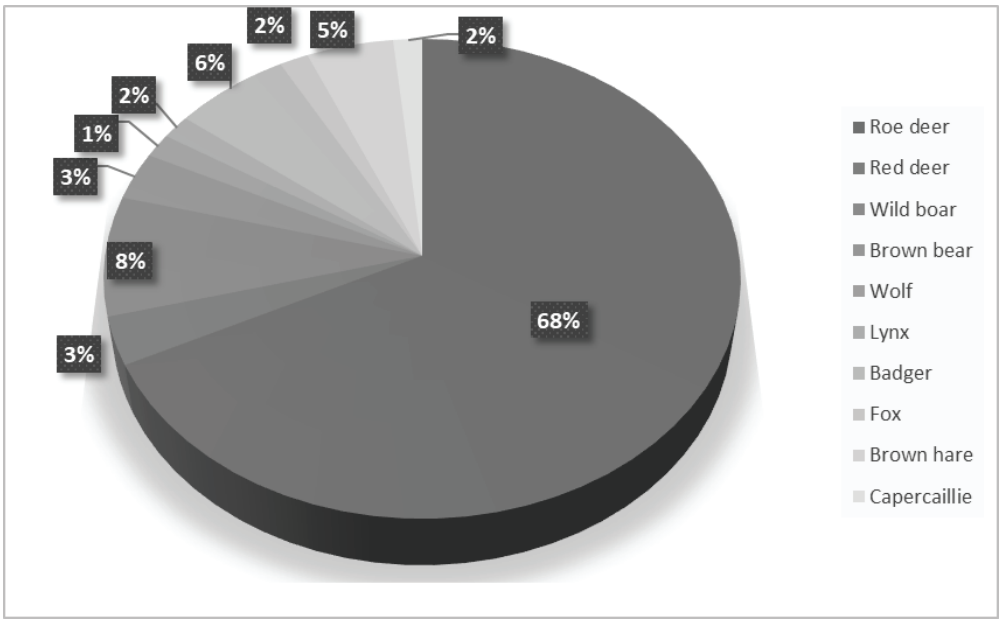


Figure 1 Wildlife-Vehicle Collisions by Species in Plitvice Lakes National Park (2017–2018)

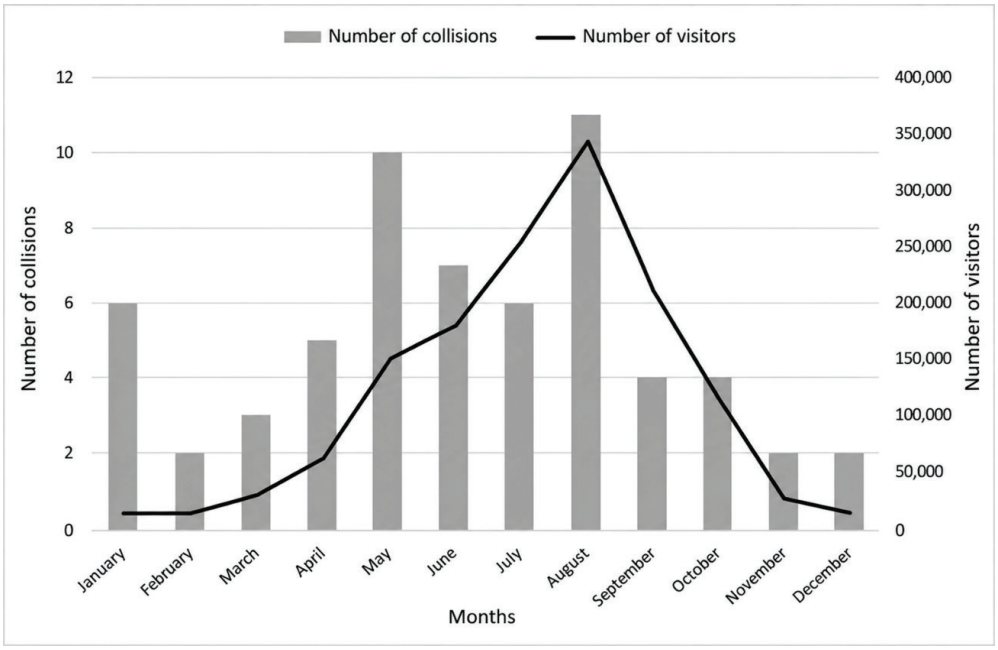


Figure 2 Monthly visitor numbers and wildlife–vehicle collisions in Plitvice Lakes National Park during 2017–2018

5. MITIGATION MEASURES

Based on the identified collision patterns, several mitigation measures are recommended. Educational campaigns targeting drivers can increase awareness of wildlife presence and improve driver behaviour in high-risk areas. Information boards, brochures and digital communication

channels may be particularly useful in a tourist destination such as Plitvice Lakes National Park. Traditional warning signs are widely used but often have limited effectiveness because drivers become accustomed to them [3]. Active warning systems triggered by animal movement offer greater potential and have shown positive results in several countries. Vegetation management along roads can improve visibility and provide drivers with more time to react. Additional measures include speed reduction in critical areas and targeted traffic management during periods of high wildlife activity. Were justified by collision frequency and ecological conditions, wildlife crossings such as ecoducts and underpasses should be considered. These structures can maintain habitat connectivity while reducing wildlife mortality. Although expensive, they represent one of the most effective long-term solutions [6]. The implementation of mitigation measures should be accompanied by continuous monitoring to evaluate effectiveness and identify emerging collision hot spots.

6. CONCLUSION

Wildlife–vehicle collisions represent an important ecological, economic and safety issue in Plitvice Lakes National Park. Roe deer were the most frequently affected species, while collisions involving protected carnivores emphasise the conservation importance of the problem. The application of GIS tools and Kernel Density Estimation successfully identified collision hot spots and priority road sections for intervention. Annual and daily patterns demonstrated the influence of wildlife behaviour and traffic intensity on collision occurrence. The proposed methodology provides a practical framework for monitoring and management. Future efforts should focus on implementing targeted mitigation measures, improving driver awareness and maintaining long-term monitoring programmes. Such actions could substantially reduce wildlife mortality, material damage and risks to human safety while contributing to biodiversity conservation in protected areas.

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Professional paper

APPLICATION OF IoT TECHNOLOGY IN WORK AND PROTECTIVE CLOTHING

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Abstract: *The development of the Internet of Things (IoT) has opened up new possibilities in the field of occupational safety, especially through the integration of smart sensors and communication modules into work and protective clothing. Such "smart clothing" enables continuous monitoring of physiological parameters of employees (body temperature, heart rate, blood oxygenation level) as well as parameters of the working environment (temperature, humidity, presence of harmful gases, exposure to noise and vibrations). The collected data is transmitted in real time to central monitoring systems, which enables timely intervention and prevention of occupational accidents and diseases. Special attention is paid to implementation challenges, such as power supply durability, protection of employees' personal data, and integration with existing safety management systems. The paper presents an overview of available technological solutions and highlights their application potential in high-risk industries.*

Keywords: *hazard prevention, real-time data transmission, safety management systems, smart clothing, wearable sensors*

1. INTRODUCTION

The Internet of Things (IoT) enables physical objects to collect and exchange data through interconnected networks, making it a transformative force in occupational health and safety. Work and protective clothing, traditionally a passive barrier against mechanical, thermal, chemical, or biological hazards, is being redefined by the integration of smart sensors and wireless communication modules. Modern smart clothing continuously monitors both the wearer's physiological state and the surrounding work environment, transmitting data in real time to centralized safety management systems. This shift from passive to active protection enables proactive hazard detection rather than reliance on periodic inspections and reactive incident response [1].

2. IoT TECHNOLOGY OVERVIEW IN OCCUPATIONAL SAFETY

IoT-based occupational safety systems rely on three core components [2]: sensing devices that measure temperature, humidity, gas concentrations, noise, vibration, heart rate, and blood oxygen saturation; communication infrastructure using BLE (Bluetooth Low Energy), ZigBee, Wi-Fi, LoRaWAN (Long Range Wide Area Network), LPWAN (Low-Power Wide-Area Network), NB-IoT (Narrowband IoT), 4G or 5G to transmit data; and data processing platforms that apply threshold rules and machine learning algorithms for real-time alerting and predictive hazard detection. Together they form an integrated system capable of continuous, individual-level occupational safety monitoring [3, 4]. No single IoT technology meets all the needs of smart workwear. Practical deployments combine BLE for body-level sensing with LoRaWAN or 4G LTE for wider connectivity, while 5G remains a future option limited by cost and infrastructure availability. Table 1 presents the characteristics of the technologies used to connect to the Internet of Things:

Table 1: IoT connectivity technologies used in smart workwear applications [5, 6, 7, 8, 9, 10]

Technology	Range	Data rate	Power use
Bluetooth Low Energy 5.x	≤ 100 m	Up to 2 Mbps	Very low
ZigBee, IEEE 802.15.4	10–100 m	250 kbps	Very low
Wi-Fi, 802.11 a/b/g/n/ac/ax	≤ 100 m	Up to 9.6 Gbps	High
LoRaWAN, LPWAN	2–15 km	0.3–50 kbps	Very low
NB-IoT, Narrowband IoT	Wide (cellular)	20 - 250 kbps	Low
4G LTE, Cellular	Wide (cellular)	Up to 150 Mbps	Medium–high
5G, Sub-6 GHz / mmWave	Wide / urban	Up to 10 Gbps	Medium

3. SMART CLOTHING: SENSORS AND COMMUNICATION MODULES

Textile-integrated temperature sensors enable continuous heat stress assessment [11, 12], critical in foundries, mining, and outdoor construction. ECG (Electrocardiogram) and PPG (Photoplethysmography) sensors measure heart rate throughout the shift [13]; combined with accelerometer data, they distinguish normal exertion from developing cardiac events. Wearable pulse oximetry monitors blood oxygen saturation (SpO_2) [13, 14], providing early warning in confined spaces or toxic gas environments [15]. Ambient temperature and humidity sensors [16, 17] assess heat stress risk as workers move across zones. Miniaturized electrochemical and metal oxide semiconductor sensors detect CO, H_2S, ammonia, VOCs, and oxygen deficiency [18, 19, 20] at the personal level, outperforming fixed-area monitors. Wearable sound level meters and accelerometers provide continuous noise and vibration exposure records [1, 21, 22], addressing leading causes of occupational hearing loss and musculoskeletal disorders.

4. REAL-TIME DATA TRANSMISSION AND MONITORING SYSTEMS

Sensor data is aggregated by a body-worn gateway in a vest, belt, or helmet, which buffers data locally and transmits it via BLE, Wi-Fi, ZigBee, LoRaWAN, or 5G [2, 23]. 5G delivers high bandwidth, low latency, and reliable coverage [2, 24] needed for large-scale wearable deployments. Monitoring platforms apply threshold rules and predictive algorithms [14, 25] to incoming streams, delivering simultaneous alerts to the affected worker's wearable device, the supervisor's mobile application, and safety officer dashboards. This parallel multi-channel delivery [2, 26] ensures rapid response regardless of personnel location, a factor that is decisive for accident prevention.

5. IMPLEMENTATION CHALLENGES

Powering smart garments through shifts of eight to twelve hours while maintaining flexibility, weight, and washability remains a core engineering challenge. LIBs (Lithium-Ion Batteries) dominate current solutions; thermoelectric generators, flexible photovoltaic cells, and kinetic energy harvesters are promising complements under research. Electronic components and textile interconnects must also survive abrasion, chemical exposure, extreme temperatures, and repeated laundering without degradation [27, 28, 29]. Continuous collection of physiological and location data raises privacy concerns: workers need assurance that health data will not be repurposed, and most jurisdictions classify it as sensitive personal data requiring explicit consent, defined retention, and restricted access [30, 31]. Wireless transmission and cloud storage introduce cybersecurity risks that demand robust encryption and authentication [31, 32]. Integrating smart clothing data with existing safety management systems requires overcoming interoperability barriers across heterogeneous platforms and legacy infrastructure [31, 33], alongside organizational change management and training to address alert fatigue and build the competencies for real-time data-driven decision-making [34].

6. APPLICATIONS IN HIGH-RISK INDUSTRIES

Mining and underground construction expose workers to simultaneous hazards - toxic gases, oxygen deficiency, extreme heat, high noise, and physical injury [35, 36] - where real-time smart garment monitoring substantially reduces the interval between hazard onset and intervention. In firefighting, IoT-enabled turnout gear that monitors core temperature, heart rate, and thermal conditions gives incident commanders real-time physiological situational awareness [37], supporting timely decisions on rotation and emergency withdrawal. In chemical and petrochemical facilities, personal gas sensors track each worker's actual micro-environment exposure across variable hazard zones [18, 20, 38], surpassing fixed monitors. In construction, smart helmets and vests with GPS (Global Positioning System), fall detection, and physiological sensors enable site-wide real-time monitoring [39, 40] and generate detailed post-incident records supporting evidence-based safety improvements [25].

7. IoT-ENABLED PROTECTIVE CLOTHING - MARKET SOLUTIONS

The market for IoT-enabled protective clothing and smart PPE has grown significantly, with solutions now available across a wide range of garment types and industrial sectors. SlateSafety's BAND V2 is an arm-worn industrial IoT device that continuously monitors heart rate, core body temperature, and exertion levels, delivering real-time heat stress alerts to both the worker and their supervisor through a cloud-based platform [41]. Blackline Safety's G7 wearables combine personal gas detection for up to five gases simultaneously with lone worker monitoring, GPS positioning, fall detection, and two-way voice communication via 4G cellular or satellite connectivity, and are deployed in over 3,000 organizations worldwide [42]. Hexoskin, developed by Carré Technologies, offers two smart garment lines: the commercial Hexoskin Smart Shirt, which embeds ECG, respiratory, and activity sensors into a washable textile garment used widely in first responder and defence applications [43], and the advanced Astroskin system, which adds SpO_2, blood pressure, and 3-lead ECG monitoring for up to 48 hours of continuous operation [44].

Triax Technologies' Spot-r Clip attaches to a worker's belt and provides fall detection, panic alerts, GPS-based location tracking, geofencing, and evacuation management through an IoT mesh network, and has been deployed in petrochemical facilities including INVISTA sites [45]. Kenzen's smart armband and patch system monitors heart rate, body temperature, and hydration levels every 15 seconds, alerting workers and safety managers in real time to prevent heat exhaustion in construction, oil and gas, and agricultural environments [46]. Guardhat, now rebranded as Aatmunn, produces a smart hardhat that integrates a camera, microphone, speaker, augmented reality display, environmental sensors, and real-time location tracking with two-way communication capabilities for industrial workers [47]. ProGlove's MARK 2 and MARK 3 smart gloves provide hands-free BLE barcode scanning with ergonomic monitoring and process confirmation feedback, and have been adopted by major manufacturers including BMW, Audi, Volkswagen, IKEA, and Bosch [48]. Intellinium's smart safety boots incorporate a patented pressure sensor membrane in the toe cap, enabling hands-free emergency distress signals and fall/impact detection with instant supervisor notification via IoT connectivity [49]. The Kinetic Reflex wearable, now integrated into the Soter Analytics platform, clips onto a worker's clothing and monitors posture and movement in real time, providing vibration feedback directly to the worker when unsafe body positions are detected to reduce musculoskeletal injury risk [50].

WakeCap's helmet-mounted sensor provides site-wide real-time worker location tracking, proximity alerts, fall detection, and attendance management through an IoT mesh infrastructure [51]. Westinghouse Nuclear's WeConnect system integrates smart hardhats, eyewear, safety tags, and clip-on sensors into a unified connected worker platform supporting emergency alerts, audio and video calls, indoor and outdoor location tracking, environmental sensing, and fall detection across nuclear facilities [52]. Moldex offers respirator masks for protection against particles, gases, and vapors, including products marketed under the Smart series [53]. MakuSafe's wearable armband continuously monitors environmental hazards including noise, temperature, air quality, and light levels alongside motion and near-miss events, with all data streamed to a cloud platform, as confirmed in a PwC case study deployment [3]. Finally, SmartCap Technologies, now part of Wenco (Hitachi Construction Machinery), produces the LifeBand - an EEG-based fatigue monitoring device integrated into a standard hard hat liner or cap which measures brainwave activity in real time and delivers progressive fatigue alerts via Bluetooth to an app and to mine control rooms [54].

8. CONCLUSION

IoT-enabled work and protective clothing marks a significant advance in occupational health and safety, transforming passive garments into active, data-driven safety systems. Core technological components such as physiological and environmental sensors, wireless communication, body-worn gateways, and centralized analytics are increasingly available and have been implemented across mining, firefighting, chemical processing, and construction. Remaining challenges in power durability, data privacy, and system integration are being addressed through research and evolving regulatory frameworks. As sensor miniaturization, energy harvesting, 5G, and AI analytics continue to advance, adoption will accelerate. Future priorities include standardized smart textile durability protocols, data governance frameworks, and a broader industrial evidence base.

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Original scientific paper

COMPARATIVE ANALYSIS OF DCT-DOMAIN STEGANOGRAPHIC ALGORITHMS FOR NIGHT-TIME JPEG IMAGES

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Abstract: *This paper demonstrates that three steganographic algorithms operating in the DCT domain of JPEG images can embed authenticity, integrity, and environmental metadata invisibly into image records while preserving visual quality. Experiments on a real-world set of nighttime camera trap images characterized by a limited color range and small file sizes at various JPEG quality levels show that AC coefficient modification enables covert data integration without perceptible changes in visual quality, color diversity, or file size.*

Keywords: *AC coefficients, camera photo-trap images, statistical image properties, steganographic capacity, visual imperceptibility*

1. INTRODUCTION

Steganography involves secretly embedding data within image files without visibly altering them. Its capacity depends on factors like image format, compression, and the algorithm used. Unlike cryptography, steganography aims to hide not just the message content, but the very existence of communication. This paper focuses on steganographically embedding contextual, sensory, and verification data [1] into JPEG images [2] collected from camera traps, with a particular focus on nighttime images. JPEG format is both challenging and useful for this purpose due to its compression method. Night images are especially complex because of low light, infrared illumination, and high noise levels, all of which affect image properties. The authors review existing literature on camera trap image processing, covering hardware effects on image quality [3], data organization workflows [4], deployment methodologies and detection reliability [5], how camera emissions can influence animal behavior during nighttime operations [6], and frameworks for correcting detection bias [7]. However, no prior work has combined steganography with nighttime camera trap images. The approach enables integrity verification and covert embedding of contextual data — such as location or timestamp — directly into image records, eliminating separate metadata files and meeting a

growing need for authenticity assurance across occupational safety and environmental monitoring applications. The paper therefore fills that gap by exploring how additional information can be embedded into such images while preserving their visual and analytical usefulness.

2. RESEARCH PROCEDURE

The paper investigates steganography as a method to embed contextual and visual data directly into camera trap image records, eliminating the need for separate metadata storage. The core focus is analyzing how different algorithms and data amounts affect the visual quality and statistical properties of nighttime JPEG images, which are characterized by infrared illumination, limited color range, and high contrast.

For the research, night images from camera traps were organized into eleven categories (bear, boar, cat, fox, horse, lynx, person, rabbit, vegetation, vehicle, venison), with 25 HD images per category. All images were compressed in JPEG at two quality levels - Q75 and Q95 - analyzed separately. Quality 75 offers higher compression with more quantization noise and fewer available AC DCT coefficients, while quality 95 provides lower compression, more detail, and greater steganographic capacity. Three DCT-domain steganographic algorithms were tested. The nsF5 algorithm [8] embeds only in non-zero AC DCT coefficients, avoids the "shrinkage" effect, is statistically harder to detect but limited in capacity, and is simple and fast. J-UNIWARD [9] is content-adaptive and targets textured or noisy areas to minimize visual and statistical impact; it achieves high undetectability but is computationally demanding. LSB DCT [10] embeds in least significant bits of non-zero AC DCT coefficients without any content adaptation, making it extremely fast but easily detectable and prone to visible artifacts. Data amounts were defined by the bpnzAC parameter at values of 0.05, 0.10, 0.20, 0.30, and 0.40.

To evaluate the impact of steganographic processing, four standard metrics were used to compare original and processed images. MSE calculates the average squared pixel difference, where lower values indicate greater similarity. PSNR represents the signal-to-noise ratio between the two images, where higher values are more desirable [11]. SSIM estimates structural similarity by accounting for brightness, contrast, and structure in a way that mimics human visual perception, with values closer to 1 indicating greater similarity [11]. ΔE2000 describes perceptual color difference, where values under 1 are invisible to the human eye and values above 10 indicate clearly visible changes [12]. Changes in unique color count and file size were additionally tracked as supplementary indicators of steganographic impact. The entire process followed five stages: image collection, night photo selection, steganographic integration across all algorithms and bpnzAC values, results analysis, and data visualization. The pipeline was implemented in Python 3.12 using libraries including Conseal 2025.11, Jpeglib 1.0.2, NumPy, Pandas, Pillow, and Scikit-image, ensuring reproducibility and transparency throughout the experimental process.

3. ANALYSIS OF RESULTS

Results for JPEG qualities 75 and 95 are presented graphically using scatter charts, where each point represents a single image and medians are connected by a line. The influence of the bpnzAC parameter on MSE, PSNR, SSIM, ΔE2000, color count difference, and file size change is analyzed

across all steganographic processing levels. Figure 1 shows graphs illustrating the influence of the bpnzAC coefficient on MSE and PSNR for the three steganographic algorithms used at both JPEG qualities. J-UNIWARD algorithm achieves the best compromise between steganographic capacity and image quality, since at all levels of the bpnzAC coefficient it has the lowest MSE values and the highest PSNR values. In contrast, LSB DCT proves to be the most aggressive method, with an increase in MSE and a significant decrease in PSNR even at moderate values of the bpnzAC coefficient. The nsF5 algorithm achieves significantly better results than LSB DCT, but it is inferior to J-UNIWARD. Higher JPEG quality (Q95) consistently reduces the level of distortion for all analyzed algorithms.

Figure 2 shows the influence of the bpnzAC coefficient on SSIM and the mean value of ΔE2000 for the same three algorithms and both JPEG qualities. J-UNIWARD best preserves the structural and perceptual characteristics of the image record, even with larger amounts of integrated data. LSB DCT causes the greatest degradation of image structure and the greatest perceptual color changes, which is reflected in the lowest SSIM values and the highest ΔE2000 values. The nsF5 algorithm is significantly better than LSB DCT but does not reach the level of J-UNIWARD. As with the previous metrics, higher JPEG quality (Q95) mitigates the negative impact of steganographic integration for all algorithms.

Figure 3 shows graphs illustrating the influence of the bpnzAC coefficient on the change in the number of colors and the size of the JPEG file for all three algorithms at both qualities. Each point represents the difference in the number of colors and the difference in the file size for a particular image, while the lines show the median values of these differences. The results show that J-UNIWARD causes virtually no change in color structure or JPEG file size, which further confirms its low statistical and perceptual salience. In contrast, LSB DCT causes drastic changes in both the number of colors and the file size. The nsF5 algorithm shows small changes on average, but extremes occasionally occur, which indicates less stability compared to J-UNIWARD. The analysis of color count and file size changes proved to be valuable auxiliary indicators for assessing steganographic processing quality. Combined with classic metrics such as MSE, PSNR, SSIM, and ΔE2000, they enable a more complete evaluation of steganographic integration's impact on image records.

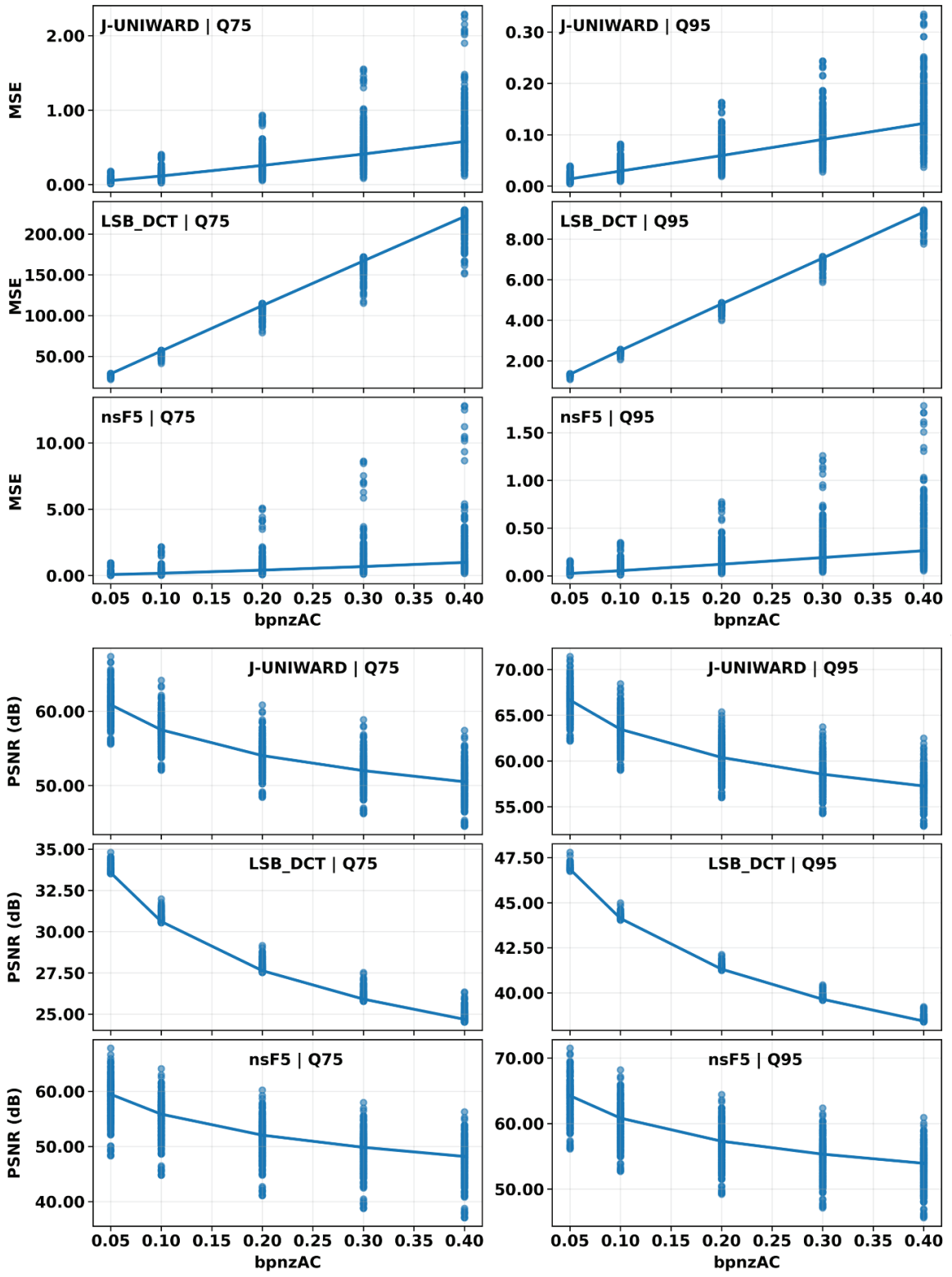


Figure 1: Numerical distortion metrics (MSE, PSNR) versus embedding intensity (bpnzAC)

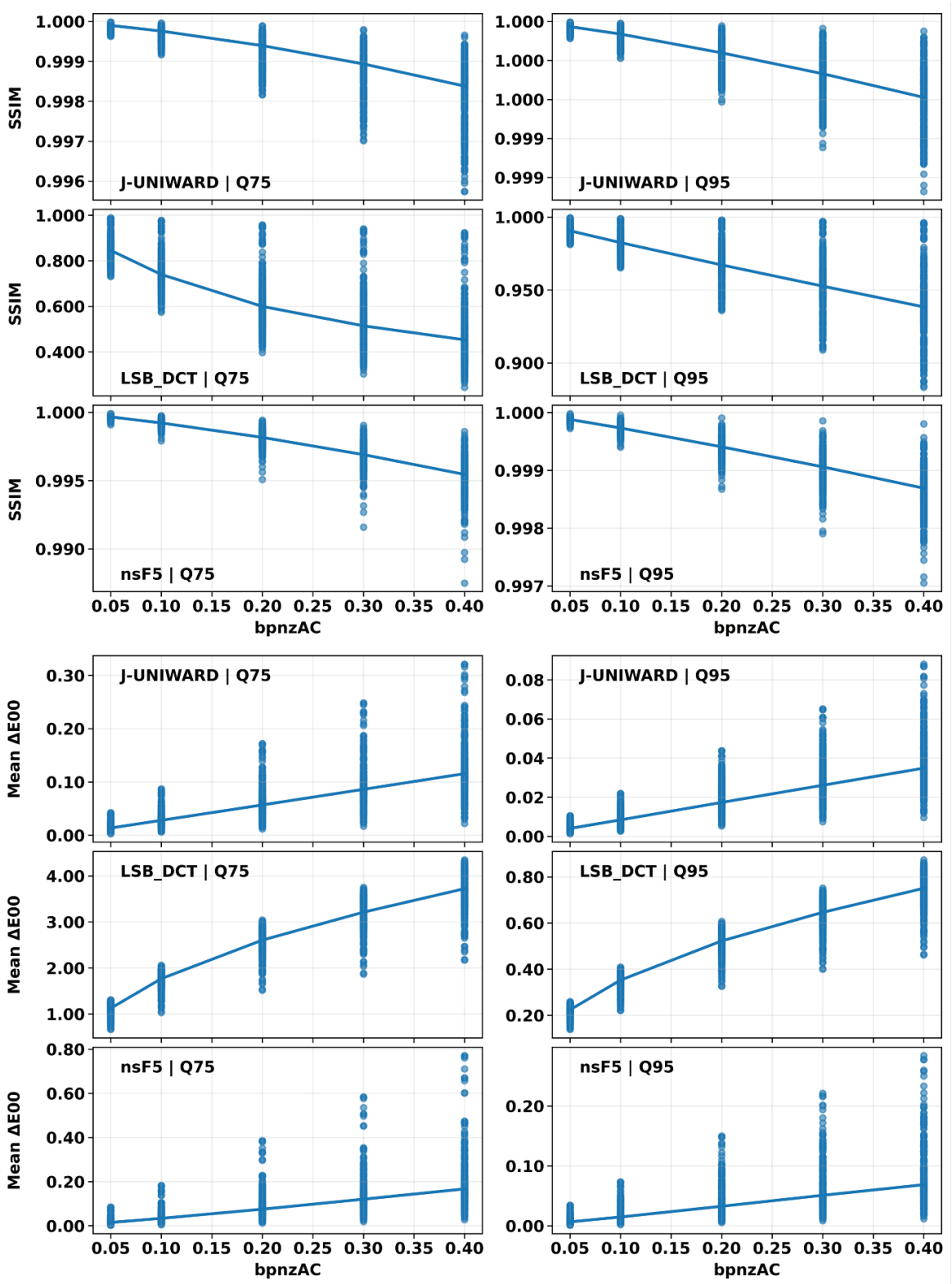


Figure 2: Structural similarity and perceptual color difference versus embedding intensity (bpnzAC)

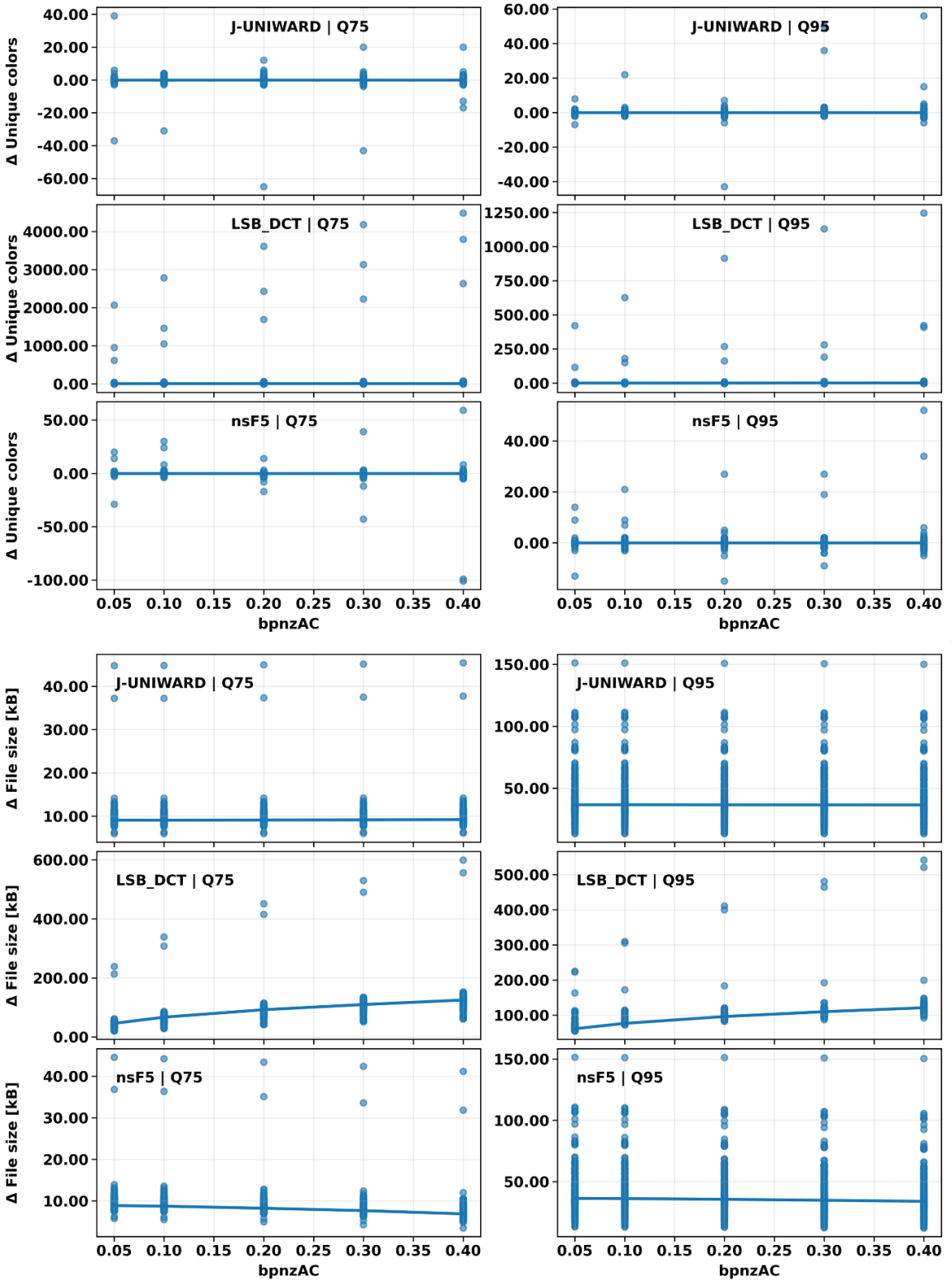


Figure 3: Changes in color diversity and file size caused by steganographic embedding (bpnzAC)

4. CONCLUSION

The research results show that J-UNIWARD achieves the lowest deviations in numerical, perceptual, and statistical metrics, thanks to content-adaptive data integration. However, such quality is achieved at the expense of high computational complexity and slow execution, which limits its application in resource-constrained or real-time systems. The nsF5 algorithm represents a good compromise between imperceptibility and efficiency, offering faster execution with moderately higher deviations. In contrast, LSB DCT causes the greatest image degradation and the highest detectability, especially at higher embedding capacities. Higher JPEG quality reduces the level of distortion for all algorithms. Future work is focused on steganalytic evaluation, extending perceptual metrics, and analyzing the impact of steganography on computer vision tasks.

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Professional paper

INTEGRATION OF IoT, SURVEILLANCE SYSTEMS AND COMPUTER VISION IN WORKPLACE HAZARD DETECTION

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Abstract: *Modern approaches to occupational safety rely on advanced technologies such as the Internet of Things (IoT), video surveillance systems and computer vision, the integration of which creates intelligent systems for real-time hazard detection. IoT sensors deployed throughout the workplace continuously collect data on the presence of hazardous substances, temperature extremes, noise levels and other environmental parameters, while surveillance cameras equipped with computer vision algorithms automatically recognize risky situations such as improper use of protective equipment, unauthorized access to dangerous zones or employees falling. The system analyzes the collected data in real time, correlates it and generates automated warnings to responsible personnel, which significantly shortens the reaction time and reduces the likelihood of an accident. The paper considers the architecture of such an integrated system, technical requirements for its implementation, and key challenges such as privacy protection, reliability of algorithms in difficult working conditions, and compliance with current European and Croatian occupational safety regulations.*

Keywords: *automated alerts, fall detection, protective equipment compliance, privacy protection, real-time hazard detection*

1. INTRODUCTION

Occupational safety remains a fundamental obligation of every modern organization. Despite advances in regulatory frameworks [1, 2, 3], workplace accidents continue to cause human suffering and significant economic losses. Traditional hazard detection has relied on periodic manual inspections and reactive measures, which are inherently limited in dynamic work environments. Recent developments in digital technologies, specifically the Internet of Things (IoT), video surveillance, and computer vision, open new possibilities for continuous, proactive monitoring. The greatest potential lies in their integration into a unified system that collects, correlates, and analyzes data from multiple sources in real time, detecting hazardous conditions as they emerge and alerting responsible personnel immediately [4, 5, 6]. This paper presents the architecture and key technical considerations for such a system, with attention to privacy protection, algorithm reliability, and compliance with European and Croatian occupational safety regulations.

2. TECHNOLOGIES OVERVIEW

IoT sensors form the primary data collection layer of an integrated safety system, continuously monitoring environmental parameters such as toxic gas concentrations, temperature, humidity, noise levels, and airborne particulates [7, 8]. Wearable sensors worn by workers complement fixed environmental sensors by tracking physiological indicators such as heart rate, body temperature, and fatigue, while detecting sudden movements consistent with falls or collisions and enabling real-time worker localization for rapid emergency response [9, 10, 11, 12, 13]. Effective deployment requires careful consideration of sensor placement, communication protocols, and redundancy to ensure reliable, low-latency data transmission even in environments with significant electromagnetic interference [14, 15, 16, 17, 18].

Modern IP (Internet Protocol) cameras with high resolution, wide dynamic range, and low-light capability are well-suited to industrial environments. Edge computing capabilities embedded in contemporary camera hardware allow initial data processing to occur locally, reducing bandwidth demands and latency, both critical for real-time hazard detection [19, 20, 21, 22]. Video management software integrates camera feeds, alert notifications, and recorded footage into a unified interface, with standardized APIs (Application Programming Interfaces) enabling interoperability with other safety and building management systems [23, 24]. Deep learning-based computer vision, particularly convolutional neural networks, enables automatic recognition of safety-relevant situations within video streams [25, 26, 27]. Key applications include PPE (personal protective equipment) compliance detection (helmets, vests, goggles, and gloves), fall detection through body pose analysis, zone intrusion detection, and identification of unsafe behaviors such as proximity violations near moving machinery. Algorithm performance depends critically on training data quality and regular retraining with site-specific data to maintain accuracy under variable industrial conditions including poor lighting, dust, and occlusion.

3. SYSTEM ARCHITECTURE

The system is organized into three functional layers [28, 29, 30]. The perception layer encompasses all IoT sensors, wearables, and cameras. The communication layer provides the network infrastructure combining wired and wireless protocols as required for reliable data transmission. The data integration layer handles preprocessing, formatting, and synchronization of heterogeneous data streams from sensors, cameras, and ancillary systems such as access control, providing standardized interfaces for downstream analytics components.

The analytics layer applies computer vision algorithms to video streams, evaluates sensor readings against thresholds, and uses data fusion techniques to correlate outputs from multiple sources. Cross-validating detection, for example, confirming a vision-detected fall with accelerometer data from a wearable, substantially reduces false alarms [13, 31, 32]. Confirmed hazards trigger automated alerts delivered via on-site alarms, mobile notifications, or integrated emergency systems, with prioritization mechanisms preventing operator overload. All events and alerts are logged for post-event analysis, trend identification, and regulatory reporting, supported by dashboards for safety managers.

4. KEY CHALLENGES

Continuous video surveillance and wearable monitoring raise significant privacy concerns. Under the EU GDPR (General Data Protection Regulation) [33], employers must establish a valid legal basis for data processing, conduct data protection impact assessments for high-risk monitoring systems, and apply stricter rules to biometric data. Workers must be clearly informed about what data is collected, for what purpose it is used, how long it is retained, and who has access to it [34]. Privacy-by-design measures, local video processing with transmission of event notifications only, and anonymization where individual identification is not required for safety purposes can substantially mitigate these risks.

Industrial environments challenge algorithm performance through variable lighting, dust, steam, vibration, and worker occlusion. Excessive false positives cause alert fatigue and erode trust in the system, while false negatives represent direct safety risks. Careful threshold calibration, site-specific model retraining, and ongoing performance evaluation are essential. System resilience must also be ensured through redundant sensors, backup communication paths, and local processing capabilities that maintain function during network outages, supported by regular sensor calibration and maintenance schedules.

Implementation must comply with Croatia's Occupational Safety Act and the EU Framework Directive, requiring systematic risk assessment, safety plan updates, worker consultation, and in some industries independent functional safety certification [35, 36, 37]. Video surveillance additionally requires informing workers, obtaining representative consent, limiting data to stated purposes, and maintaining access logs.

5. COMMERCIAL PLATFORMS FOR WORKPLACE HAZARD DETECTION

A growing number of commercial platforms combine real-time video analytics, artificial intelligence, and IoT sensor infrastructure to detect workplace hazards, monitor compliance, and generate automated alerts. Intenseye [38] is a computer vision safety platform that operates on existing CCTV (closed-circuit television) infrastructure without additional hardware. It offers over 45 pre-built AI rules covering PPE detection, fall detection, ergonomic risk, and zone intrusion, and delivers real-time SIF (Serious Injury and Fatality) risk scoring to EHS (Environment, Health and Safety) teams. Protex AI [39] connects to existing CCTV via an on-site edge processing device, analyzing video locally and transmitting only anonymized event metadata to a cloud dashboard. It supports custom safety rules, PPE compliance, near-miss detection, and ergonomic assessment. Voxel AI [40] is a site intelligence platform trained on over five billion hours of industrial workplace scenarios, deployable within 48 hours using existing cameras. It detects PPE violations, vehicle-pedestrian proximity risks, spills, and blocked exits, converting events into trackable corrective actions. viAct [41] combines computer vision with IoT sensor data for continuous monitoring in construction, manufacturing, and industrial environments. It covers PPE compliance, restricted zone monitoring, fall detection, and fire and smoke recognition. A generative AI component creates and adapts site-specific safety plans in real time, with immediate alerts delivered to supervisors upon hazard detection. Sentri360 [42] fuses computer vision, real-time location services, and IoT wearable sensors into an edge-based safety

architecture for demanding environments including oil and gas, and shipbuilding. Key capabilities include geofencing-based hazard zone detection, fatigue monitoring, and customizable machine learning safety protocols, designed to shift safety management from reactive to proactive.

Surveily [43] is an AI video analytics platform compatible with approximately 95% of existing digital cameras. It provides real-time hazard detection, automated compliance monitoring, and a dashboard pre-loaded with customizable industry-standard safety rules, covering the full workflow from detection through alert generation to incident reporting. Visionify [44] transforms existing IP cameras into a safety monitoring system with over 50 pre-built AI event models for PPE, zone monitoring, near-miss, and fire detection. It is compatible with cameras from over 500 manufacturers and delivers full deployment within two to three weeks, with 24/7 monitoring and OSHA-aligned (Occupational Safety and Health Administration) compliance reporting. Spotr AI [45] is a visual intelligence platform for large-scale or geographically dispersed industrial sites where fixed cameras are impractical. Using drone-based and camera-based inspections, it identifies safety risks in energy, construction, and logistics environments, and integrates hazard detection with predictive maintenance and automated compliance reporting. Honeywell Forge [46] is an enterprise IoT platform that unifies environmental sensor data (temperature, gas detection, air quality) with the Honeywell Digital Video Manager surveillance system under a single interface. It supports remote monitoring, predictive maintenance, and automated incident response, integrating with existing IT (Information Technology) and OT (Operational Technology) systems via the Niagara Framework. Bosch IVA Pro [47] integrates AI video analytics directly into Bosch IP cameras as an edge computing solution. The PPE module detects missing safety vests and hard hats with automated alerts, while the broader suite covers person and vehicle detection, zone intrusion, and loitering. It integrates with Bosch BVMS (Bosch Video Management System) and third-party VMS (Video Management System) platforms via ONVIF (Open Network Video Interface Forum).

StrongArm Technologies [48] provides the SafeWork Platform, which combines IoT wearable sensors with an AI-powered analytics dashboard to detect and prevent ergonomic injuries in warehouses, logistics, and industrial environments. The back-worn sensor monitors high-risk movements in real time, delivers haptic feedback to workers, and feeds biomechanical data to managers for proactive intervention. Arvist AI [49] is a computer vision platform that transforms existing warehouse security cameras into autonomous safety and compliance monitors. It detects PPE violations, forklift-pedestrian proximity hazards, improper lifting, fallen persons, and spills in real time, generating timestamped video clips and automated incident reports. The platform uses Large Video Models and continuously refines its detection algorithms through machine learning. Invigilo AI [50] is an AI video analytics platform that integrates with existing CCTV infrastructure to detect over 35 safety risks in real time, including PPE violations, dangerous proximity to machinery, work-at-height hazards, and unauthorized zone intrusion. Rapid Global [51] offers Rapid Monitor, an AI computer vision module that connects to existing IP cameras to detect PPE non-compliance, dangerous forklift-pedestrian proximity, unauthorized zone access, and downed workers. The platform integrates with Rapid's broader EHS suite covering access control, contractor management, and incident reporting, providing end-to-end site safety management from a single dashboard. Chooch AI [52] is a computer vision platform purpose-built for EHS teams, providing real-time detection of PPE compliance, restricted zone intrusion, fall events, line-of-fire hazards, fire and smoke, and ergonomic risks from existing camera infrastructure. It processes video feeds continuously to deliver instant alerts and integrates with existing fire detection and alarm systems for automated emergency response.

6. CONCLUSION

Integrating IoT sensors, video surveillance, and computer vision provides a technically sound approach to proactive workplace hazard detection, offering coverage and response speed far beyond traditional manual methods. Realizing these benefits requires thorough attention to algorithm reliability in real-world conditions, privacy-by-design implementation, and compliance with applicable occupational safety and data protection regulations throughout the system lifecycle. Continued advances in deep learning, edge computing, and sensor miniaturization will further lower adoption barriers, and future work should focus on standardized architectures and evaluation methodologies to support responsible, evidence-based deployment across diverse industrial settings.

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APPLICATION OF ELECTROMYOGRAPHIC SIGNALS FOR REAL-TIME CONTROL OF ROBOTIC SYSTEMS

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Abstract: *This paper presents the development and experimental validation of a low-cost system for controlling robotic platforms using electromyographic (EMG) signals acquired through surface electrodes. The proposed approach enables intuitive human–machine interaction without conventional input devices, making it suitable for assistive applications, rehabilitation concepts, and operation in hazardous environments. Emphasis is placed on affordability and accessibility, allowing the system to serve as a demonstrational and educational platform for human–robot interaction research. As a case study, the system is implemented and evaluated on a mobile robotic platform to demonstrate real-time control performance under different operating conditions. Experimental results confirm the feasibility of the proposed solution within the constraints of a low-cost hardware setup. The work integrates concepts from biomedical engineering, embedded systems, and robotics, highlighting its potential as a scalable solution for broader robotic control applications.*

Keywords: *human–machine interaction, electromyography (EMG), low-cost systems, robotic control*

1. INTRODUCTION

Electromyography (EMG) is a widely used technique for monitoring the electrical activity generated by skeletal muscles. Surface electromyography enables non-invasive acquisition of muscle activation signals through electrodes placed on the skin, making it suitable for applications in biomedical engineering, rehabilitation, prosthetics, and human–machine interaction systems [1]. When a voluntary muscle contraction is initiated, electrical impulses generated by the central nervous system propagate through motor neurons and activate muscle fibers, producing measurable electrical potentials on the skin surface. Recent advances in electronics, embedded systems, and signal processing technologies have significantly expanded the range of practical EMG applications. In addition to their traditional use in medical diagnostics and rehabilitation, EMG signals are increasingly employed for the control of external devices, including robotic manipulators, mobile robots, prosthetic limbs, and assistive

technologies. Such systems enable intuitive interaction by translating muscle activity directly into control commands, thereby creating a natural communication channel between humans and machines [2]. The growing availability of low-cost microcontrollers, wireless communication modules, and open-source development platforms has further facilitated the implementation of EMG-based control systems outside specialized laboratory environments. As a result, affordable experimental platforms can now be developed for research, educational, and demonstrational purposes while still providing meaningful insight into the principles of bioelectrical signal acquisition and robotic control.

This paper presents the development and experimental validation of a low-cost EMG-based control system for real-time operation of a mobile robotic platform. The proposed solution combines surface electrodes, signal conditioning electronics, embedded processing, and wireless communication into a functional human–machine interface capable of converting muscle activity into robot control commands. Experimental testing was conducted to evaluate the feasibility and reliability of the developed system under real-time operating conditions. The presented prototype demonstrates how low-cost hardware can be used to implement an effective EMG-controlled robotic system while providing a suitable platform for future research and educational activities in the fields of biomedical engineering and robotics.

2. EMG SIGNAL ACQUISITION AND CONTROL SYSTEM

The developed system consists of four main functional units: EMG signal acquisition, signal conditioning, embedded signal processing, and wireless communication with a mobile robotic platform. Surface electrodes positioned on the user's forearm are used to detect the electrical activity generated during voluntary muscle contractions. Since the amplitude of EMG signals is typically very low and highly susceptible to environmental interference, appropriate amplification and filtering stages are required before further processing can be performed.

The first stage of signal acquisition is based on the INA106 instrumentation amplifier, selected because of its high input impedance, low output impedance, and effective common-mode noise rejection. These characteristics enable reliable amplification of low-amplitude differential signals generated by muscle activity while suppressing unwanted disturbances originating from the surrounding environment and power-line interference. The amplified signal is subsequently processed using multiple stages based on TL072 operational amplifiers. In the developed system, these stages are used for additional amplification, signal rectification, and filtering, resulting in a stable voltage signal suitable for digital processing. This approach allows the raw EMG signal to be transformed into a form that can be reliably interpreted by the control electronics.

Signal processing and control functions are performed by an Arduino Uno microcontroller. The conditioned EMG signal is continuously monitored through an analog input and converted into a digital value using the integrated analog-to-digital converter. The control algorithm is based on threshold detection, where measured signal levels are compared with predefined reference values in order to distinguish between muscle contraction and resting conditions. This simple but effective approach enables real-time generation of control commands without the need for complex signal-processing algorithms.

Wireless communication between the control unit and the robotic platform is established using an HC-05 Bluetooth module. The module operates as a serial communication interface and enables transmission of control commands generated by the microcontroller to the mobile robot. In

the implemented prototype, detected muscle contractions are translated into motion commands, allowing intuitive robot control through forearm muscle activity. The EMG signal acquisition and conditioning circuit used in the developed system is presented in Figure 1.

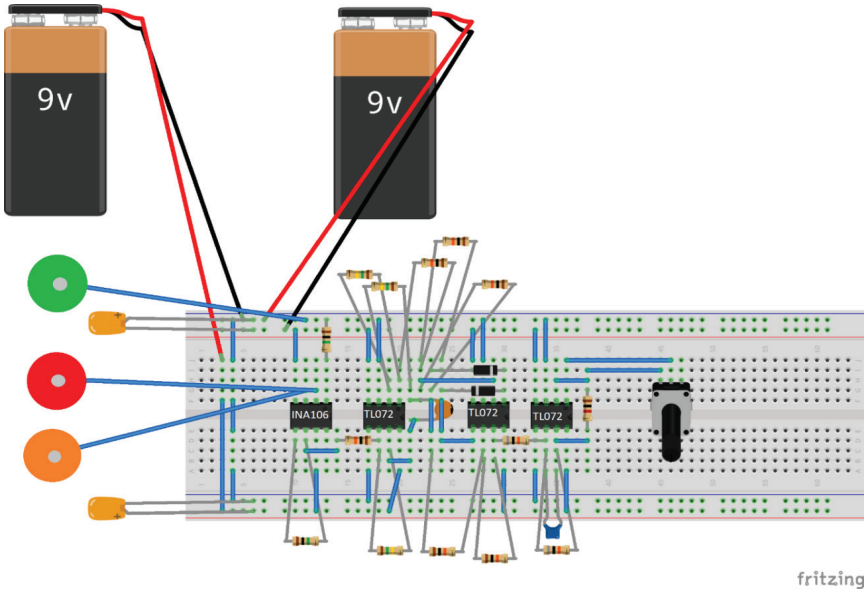


Figure 1: Electronic circuit for EMG signal acquisition and conditioning [3]

3. PROTOTYPE DEVELOPMENT AND EXPERIMENTAL VALIDATION

Following the integration of all hardware and software components, an experimental prototype was assembled to evaluate the performance of the developed EMG-based control system. The prototype consists of the EMG signal acquisition and conditioning circuit, an Arduino Uno microcontroller, an HC-05 Bluetooth communication module, and a mobile robotic platform. All electronic components were interconnected on a prototyping platform and configured to enable real-time acquisition, processing, and wireless transmission of EMG signals. The completed experimental setup is shown in Figure 2.

Experimental testing was performed using surface electrodes placed on the user's forearm above the muscles responsible for hand and finger movement. During operation, muscle contractions generate low-amplitude electrical signals that are detected by the electrodes and processed through the amplification and filtering stages described in the previous section. The conditioned signal is continuously monitored by the microcontroller, which evaluates its amplitude relative to a predefined activation threshold. Proper positioning of the electrodes and adjustment of the threshold level were found to be important factors affecting signal stability and control reliability.

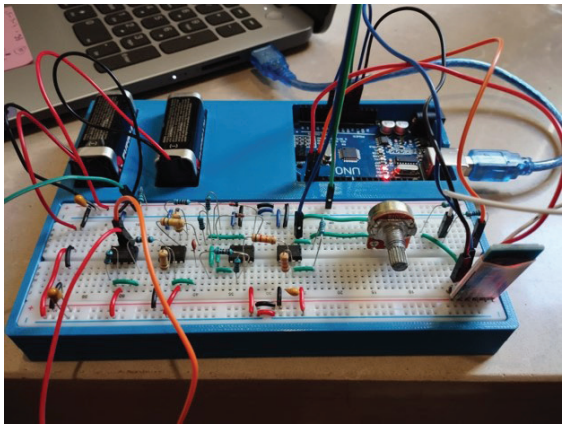


Figure 2: Experimental prototype of the EMG-based robotic control system [3]

The first stage of validation focused on analyzing the system response under different muscle activation conditions. Measurements were performed both in a relaxed state and during voluntary muscle contractions. Representative signal responses obtained during testing are shown in Figure 3. When the forearm muscles remained relaxed, the measured signal level stayed below the activation threshold and no control command was generated. During muscle contraction, a clear increase in signal amplitude was observed, resulting in reliable activation of the control logic. The results confirmed that the implemented signal conditioning circuit provided sufficient amplification and noise suppression to enable stable distinction between resting and active muscle states.



Figure 3: EMG signal response below and above the activation threshold [3]

After successful verification of signal acquisition and processing, the wireless communication subsystem and robotic platform were evaluated. The Arduino microcontroller generated control commands based on the detected EMG activity and transmitted them through the HC-05 Bluetooth module to the mobile robot. The communication link operated reliably throughout the experiments, enabling real-time transfer of control signals without noticeable delays. Depending on the detected muscle activity, the robot executed predefined movement commands, demonstrating successful translation of biological signals into physical motion.

Figure 4 presents the robotic platform during experimental testing. The results showed that voluntary muscle contractions could be consistently used to initiate robot actions, while the absence of muscle activity resulted in a stationary state. The developed system therefore successfully demonstrated the complete control chain, from acquisition of bioelectrical signals generated by muscle activity to wireless transmission and execution of movement commands on the robotic platform.

The conducted experiments confirmed the feasibility of implementing an EMG-based robotic control interface using readily available and low-cost hardware components. Although the developed prototype was intended primarily as a demonstrational and educational platform, the obtained results indicate that the proposed approach can serve as a basis for further research in human–machine interaction, assistive technologies, and EMG-based robotic control systems.

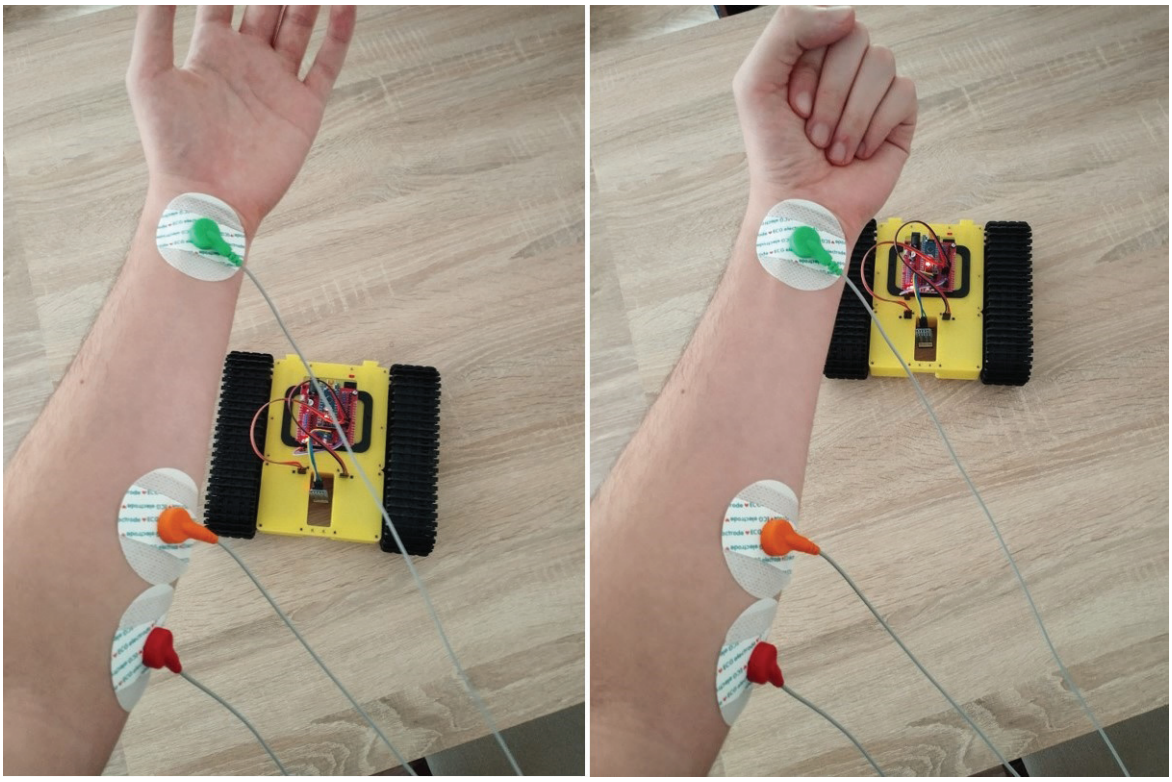


Figure 4: Experimental validation of robot control using EMG signals acquired from forearm muscles [3]

5. CONCLUSION

This paper presented the development and experimental validation of a low-cost EMG-based control system for real-time operation of a mobile robotic platform. The proposed solution successfully integrates EMG signal acquisition, signal conditioning, embedded processing, and wireless communication into a functional human–machine interface capable of translating muscle activity into robot control commands. Experimental results confirmed reliable detection of muscle contractions, stable communication, and successful execution of robotic control commands under laboratory conditions. The obtained results demonstrate the feasibility of using low-cost hardware for intuitive EMG-based robotic control and highlight the potential of such systems for educational, research, and assistive technology applications. Future work will focus on advanced signal-processing techniques and the implementation of multiple control commands based on different muscle activation patterns. The developed prototype also contributes to ongoing educational and research activities within the iEduBot project.

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Review article

THE USE OF ARTIFICIAL INTELLIGENCE IN THE OCCUPATIONAL SAFETY AND HEALTH SYSTEMS IN THE REPUBLIC OF SLOVENIA

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Abstract: *Artificial intelligence (AI) is becoming a key driver of the digital transformation of occupational safety and health (OSH) systems, enabling more effective hazard identification, risk prediction, and decision support for preventive measures. The aim of this paper is to review publicly available literatures on the use of AI in OSH systems and to analyze their alignment with the regulatory framework in the field of occupational safety and health in the Republic of Slovenia. The results show a rapid increase in research since 2020 in the areas of machine learning, computer vision, wearable technologies, the Internet of Things, and predictive analytics. The findings confirm a shift from reactive to proactive, data-driven safety management. AI can significantly support the implementation of these obligations, but it does not replace human responsibility. The legal analysis shows that the Slovenian regulatory framework enables the use of artificial intelligence, while responsibility for ensuring a safe and healthy working environment remains with the employer.*

Keywords: *artificial intelligence, occupational safety and health, legal framework, Republic of Slovenia*

1. INTRODUCTION

Digital transformation of working environments driven by Industry 4.0 technologies, the Internet of Things (IoT), Big Data, and artificial intelligence (AI) is significantly changing approaches to occupational safety and health (OSH). Traditional safety management systems were mainly based on post-incident analysis, while modern approaches increasingly rely on real-time monitoring of work processes, risk prediction, and data-driven decision-making [2][3] [7][11].

Artificial intelligence enables the use of machine learning methods, computer vision, wearable technologies, and intelligent decision-support systems that improve hazard identification, monitoring of employee safety behavior, and risk assessment [8][9][10]. These solutions contribute to early detection of deviations and more efficient planning of preventive measures.

At the same time, AI raises important issues regarding legality, algorithm transparency, personal data protection, and accountability for decisions made [3][15]. In Slovenia, the fundamental legal framework is provided by the Occupational Safety and Health Act (ZVZD-1), which defines employers' obligations regarding risk assessment, preventive measures, and ensuring a safe working environment [19]. Although the law does not explicitly regulate AI, digital technologies can significantly support compliance with legal requirements.

The purpose of this paper is to analyze, based on a review of bibliometric studies, the development of AI in OSH systems and to present the connection between modern AI technologies and the regulatory framework of the Republic of Slovenia.

2. METHODOLOGY

This paper is based on a qualitative review of publicly available scientific literature, including bibliometric studies, systematic literature reviews, scientific articles, international reports, standards, and relevant legal documents addressing the application of artificial intelligence (AI) in occupational safety and health (OSH). The literature search was conducted in June 2026 using the Scopus, Web of Science, and Google Scholar databases. Additional searches were performed in relevant institutional and regulatory sources, including the European Agency for Safety and Health at Work (EU-OSHA), International Labour Organization (ILO), European Commission, EUR-Lex, and the Slovenian legal information system (PISRS).

The literature search focused primarily on publications from 2020 to 2026, reflecting the increasing research activity related to artificial intelligence, digitalisation, and occupational safety and health. Earlier publications were also included where they addressed specific AI-related technologies relevant to OSH, such as wearable technologies, computer vision, the Internet of Things (IoT), and automated safety monitoring.

The main keywords used in the search were "artificial intelligence", "AI", "machine learning", "deep learning", "computer vision", "predictive analytics", "wearable technology", "Internet of Things", "IoT", "occupational safety", "occupational health", "occupational safety and health", "OSH", "workplace safety", "risk assessment", "accident prevention", "worker monitoring", and "fatigue detection".

The principal keyword combinations were:

- "artificial intelligence" AND "occupational safety and health"
- "artificial intelligence" AND "occupational safety"
- "artificial intelligence" AND "occupational health"
- "machine learning" AND "occupational safety"
- "computer vision" AND "workplace safety"
- "predictive analytics" AND "occupational safety"
- "wearable technology" AND "occupational safety and health"
- "Internet of Things" AND "occupational safety"
- "artificial intelligence" AND "risk assessment"
- "artificial intelligence" AND "accident prevention"
- "artificial intelligence" AND "worker monitoring"
- "artificial intelligence" AND fatigue AND workplace

In addition, searches concerning the regulatory dimension used combinations such as “ZVZD-1” AND “artificial intelligence”, “Slovenia” AND “occupational safety” AND “artificial intelligence”, “Artificial Intelligence Act” AND workplace, “AI Act” AND “worker monitoring”, and “AI Act” AND “occupational safety”.

The literature used in the analysis included the bibliometric and interpretative review by Tamascelli et al. [17], which examines research developments in artificial intelligence, safety and reliability, as well as the review by Shah and Mishra [15], which provides an overview of developments and applications of AI in occupational health and safety. The review also considered the systematic review by Jetha et al. [11], which specifically investigated whether AI-based OSH tools have measurable effects on worker injury or illness. In addition, relevant evidence concerning wearable technologies, IoT, computer vision and automated safety applications was obtained from the studies by Awolusi et al. [1], Fang et al. [5], Sisinni et al. [16], and Tixier et al. [18]. Institutional and professional perspectives were obtained from EU-OSHA [2], the International Labour Organization [7], and relevant ISO standards, including ISO/IEC TR 24028:2020 [8], ISO/IEC 42001:2023 [9], and ISO 45001:2018 [10].

The selection and synthesis of the literature focused on four main analytical areas: (1) research trends and the development of AI applications in OSH; (2) the main AI technologies and their application areas, including hazard identification, risk assessment, accident prevention and worker monitoring; (3) organisational, ethical and technological issues, including data quality, transparency, explainability and human oversight; and (4) the relationship between AI applications and the Slovenian and European regulatory framework.

For the legal analysis, the Occupational Safety and Health Act (ZVZD-1) [19], the General Data Protection Regulation (GDPR) [13], and Regulation (EU) 2024/1689 – Artificial Intelligence Act [14] were examined. The analysis focused on the extent to which AI applications can support existing OSH obligations and on the legal requirements that may arise from the processing of workers’ data, monitoring of workers, and the use of AI systems in the workplace.

The retrieved literature was analysed qualitatively by comparing findings across the identified studies and sources. Particular attention was given to recurring research themes, technological applications, reported benefits and limitations, and the implications for OSH management. The findings of existing bibliometric studies were therefore used as a basis for identifying research trends, rather than performing a new bibliometric analysis of the retrieved Scopus or Web of Science records.

No original bibliometric analysis using Bibliometrix, VOSviewer, or equivalent bibliometric software was performed in this study. The paper therefore presents a qualitative synthesis of existing bibliometric and systematic literature studies, complemented by an analysis of the Slovenian and European regulatory framework.

3. BIBLIOMETRIC TRENDS IN ARTIFICIAL INTELLIGENCE RESEARCH IN OCCUPATIONAL SAFETY AND HEALTH

Recent bibliometric studies show a significant increase in scientific publications on AI applications in OSH systems after 2020. This growth is closely linked to digital transformation, Industry 4.0 technologies, the Internet of Things (IoT), machine learning, and increased availability of workplace

data [2][7][11][15][17]. The field is highly interdisciplinary, combining occupational safety, computer science, industrial engineering, ergonomics, and risk management.

Bibliometric analyses indicate that the dominant research areas include machine learning, deep learning, computer vision, IoT, wearable technologies, and predictive analytics. In recent years, there has been increasing interest in explainable AI (XAI), human-centered AI, and digital transformation, reflecting a shift from algorithm development to practical implementation in OSH management systems [2][7][11][15].

The literature also shows a change in research focus. While earlier studies concentrated on hazard detection algorithms, more recent studies emphasize their integration into comprehensive OSH management systems that enable real-time monitoring, risk prediction, and decision support for preventive actions [2][7][11][15][17].

Important research topics also include data quality, algorithm explainability, data privacy, and compliance with legal and ethical requirements. Bibliometric studies confirm a transition from reactive approaches based on past accidents to proactive, data-driven risk management aimed at early hazard detection and injury prevention [2][3][7][11][15][17].

4. APPLICATION AREAS OF ARTIFICIAL INTELLIGENCE IN OCCUPATIONAL SAFETY AND HEALTH

Current literature shows that AI is becoming an important component of OSH systems in industry, construction, logistics, energy, and other high-risk sectors. Common features of modern solutions include the use of data for real-time hazard detection, dynamic risk assessment, and decision support for preventive measures [2][7][11][15][17].

One of the most important technologies is computer vision, which uses cameras and deep learning algorithms to automatically detect unsafe situations, monitor personal protective equipment usage, track machinery movement, detect falls, and identify entry into hazardous areas [5][15].

Machine learning methods are also widely used to develop predictive risk models based on historical accident data, working conditions, and organizational factors. These models enable more efficient planning of preventive activities and targeting of inspections to high-risk areas [11][15][18].

Additional opportunities are provided by the Internet of Things (IoT) and wearable technologies, which enable continuous monitoring of workplace conditions and employees' physiological and ergonomic indicators. Sensors monitor temperature, air quality, hazardous gases, heart rate, posture, and fatigue, while AI algorithms analyze these data in near real time and detect deviations [1][2] [7][16].

AI also plays an important role in risk assessment by enabling a shift from periodic to dynamic assessment. By analyzing data from sensors, information systems, video surveillance, and wearable devices, systems can identify changes in working conditions and generate predictive models for preventive action. However, literature emphasizes that AI results serve as decision support, while responsibility for risk assessment and decision-making remains with employers and OSH professionals, in accordance with ZVZD-1 [11][15][19].

Regardless of the technology used, research consistently highlights that the effectiveness of AI systems depends not only on algorithms but primarily on data quality, organizational processes, and active involvement of OSH professionals in development and interpretation [2][3][7][11][15][17].

5. SLOVENIAN AND EU REGULATORY FRAMEWORK

The Occupational Safety and Health Act (ZVZD-1) establishes the employer as the central duty holder. Article 17 requires the employer to assess in writing the risks to which workers are or could be exposed and to prepare the statement of safety. This creates a direct point of connection with AI: an AI system may contribute data, pattern recognition or predictive support to the risk-assessment process, but the legal duty remains with the employer [9].

The relationship between AI functionalities, OSH obligations and regulatory governance is illustrated in Figure 1. AI can support hazard detection, risk prediction, monitoring and decision-making, while the OSH framework requires risk assessment, preventive measures, training and continuous improvement. These functions must be embedded within an appropriate governance framework based on ZVZD-1, GDPR, the EU AI Act and human oversight.

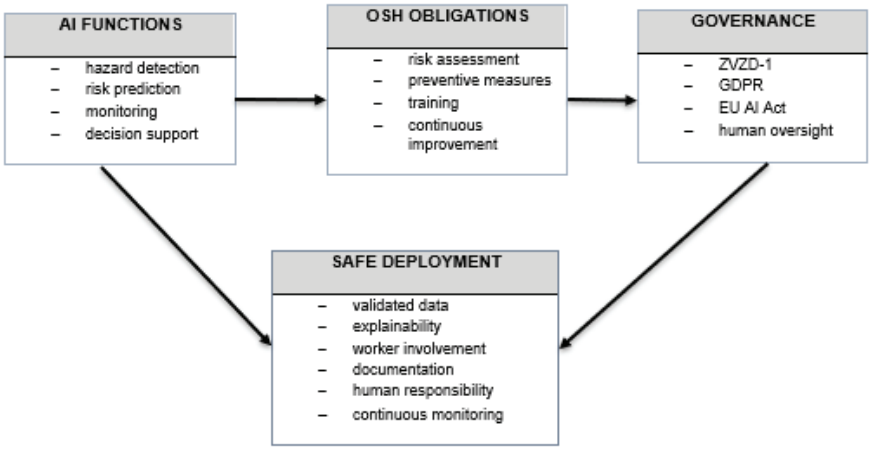


Figure 1: Conceptual framework linking AI functions, OSH obligations and regulatory governance.

The use of AI also interacts with data-protection requirements. Systems based on cameras, wearables or physiological sensors may process personal data and, depending on the data and purpose, special categories of personal data. The principles of lawfulness, transparency, purpose limitation and data minimisation under the GDPR therefore need to be considered before deployment [6].

The practical relationship between OSH obligations, potential AI functionalities, associated risks and regulatory safeguards is presented in Table 1. The table demonstrates that AI should primarily be considered as a decision-support and risk-management tool rather than as a replacement for the employer's legal and organisational responsibilities.

Table 1: AI functionalities in relation to OSH obligations, risks and regulatory safeguards

OSH obligation / need	Potential AI functionality	Main risk	Regulatory / governance safeguard
Risk assessment (ZVZD-1 Art. 17)	Predictive analytics; anomaly detection; sensor data integration	Model error; incomplete data	Human validation; documented methodology; periodic review
Hazard identification	Computer vision; IoT; automated alerts	False positives/negatives; surveillance	Proportionality; validation; worker information
Preventive measures	Decision support; risk prioritisation	Automation bias; inappropriate recommendations	Competent human decision-maker; audit trail
Worker monitoring	Wearables; video; behavioural analytics	Privacy; excessive monitoring	GDPR principles; purpose limitation; transparency
Fatigue/safety monitoring	Physiological or physical-state detection	Misclassification; intrusive use	Assess AI Act Art. 5 scope; safety purpose; human oversight
Performance/behaviour evaluation	Worker scoring; task allocation	Discrimination; algorithmic management	AI Act Annex III point 4 where applicable; governance and impact assessment

The AI Act adds a risk-based layer. Article 5 prohibits certain AI practices, including systems intended to infer emotions of natural persons in the workplace, except where the system is intended for medical or safety reasons [7]. This is directly relevant to proposals for fatigue or safety-behaviour monitoring: fatigue detection should not automatically be treated as prohibited emotion recognition, because the Act expressly distinguishes physical states such as fatigue from emotion recognition. However, the purpose, data used and functionality of the specific system must be assessed carefully.

Article 6 establishes the classification rules for high-risk AI systems, including systems listed in Annex III [7]. Annex III point 4 covers certain AI systems used in employment and worker management, including systems used to make decisions concerning work relationships, allocate tasks based on individual behaviour or personal characteristics, or monitor and evaluate performance and behaviour. Consequently, an AI system introduced for OSH purposes may also create high-risk implications if its functionality crosses into worker-management or performance evaluation.

For high-risk systems, the AI Act establishes requirements concerning risk management, data governance, documentation, transparency, human oversight, accuracy, robustness and cybersecurity. The practical consequence is that OSH deployment should be governed by a documented process that evaluates both safety benefits and risks to workers' rights.

6. DISCUSSION

The reviewed literature confirms that AI is becoming a key factor in the development of modern OSH systems. Bibliometric studies and systematic reviews consistently show that machine learning, computer vision, IoT, and predictive analytics improve hazard identification, risk assessment, and preventive planning [2][3][7][11][15][17].

The research focus is shifting from individual algorithm development to their integration into OSH management systems. Alongside technical solutions, organizational, ethical, and legal aspects are becoming increasingly important, particularly algorithm explainability, data quality, privacy protection, and human oversight [6][8][10][12][15].

Legal analysis shows that ZVZD-1 allows the use of digital technologies in OSH management, but does not transfer responsibility to AI systems. The EU AI Act similarly requires risk management, data quality, transparency, and human oversight for high-risk systems [13][14][19].

A limitation of this study is that it is based on a review of existing bibliometric studies rather than original bibliometric analysis. However, it provides a comprehensive overview of the field and a foundation for future empirical research.

7. CONCLUSION

The development of artificial intelligence is significantly transforming occupational safety and health management approaches. Bibliometric and systematic reviews show a strong increase in research activity, particularly in machine learning, computer vision, IoT, wearable technologies, and predictive analytics. These technologies support early hazard detection, improved risk assessment, and preventive planning.

The literature confirms a shift from reactive to proactive, data-driven OSH management. However, AI cannot replace professional judgment or employer responsibility; its effectiveness depends on data quality, system design, and responsible use.

The Slovenian legal framework allows the use of digital technologies in OSH, provided that they support safe and healthy working conditions. The broader EU regulatory framework, including GDPR and the AI Act, emphasizes transparency, data quality, human oversight, and responsible AI use [4][12][14].

Future research should focus on evaluating real-world impacts of AI on injury reduction, developing explainable and trustworthy systems, and improving integration into OSH management systems.

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Review article

MESHTASTIC LORA MESH NETWORK AS AN EMERGING PLATFORM FOR OCCUPATIONAL SAFETY AND HEALTH MONITORING IN INFRASTRUCTURE-DEFICIENT ENVIRONMENTS

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Abstract: *Reliable real-time communication is a fundamental prerequisite for effective occupational safety and health (OSH) management, yet many high-risk work environments—including underground mines, remote con-struction sites, forestry operations, and disaster-response zones—lack the cellular or Wi-Fi infrastructure upon which conventional monitoring systems depend. This paper examines the applicability of Meshtastic, an open-source, decentralised LoRa-based mesh networking protocol, as a low-cost and infrastructure-independent com-munication backbone for OSH applications. The paper is a narrative review and conceptual feasibility analysis based on published literature, technical documentation, and reported deployments. We review the architecture of Meshtastic protocol, survey existing LoRa-based safety research in hazardous industries, and map the protocol's features against OSH communication requirements. Key use cases examined include real-time environmental haz-ard monitoring, lone worker GPS tracking, emergency SOS alerting, and wearable sensor telemetry. Limitations of the technology—including bandwidth constraints, network scalability ceilings, and a partial security model—are critically assessed. We conclude that Meshtastic represents a compelling, low-barrier complement to existing OSH infrastructure, and propose a framework for systematic pilot deployment and evaluation.*

Keywords: *LoRa; mesh networking; Meshtastic; occupational safety and health; lone worker protection*

1. INTRODUCTION

Occupational injury and illness remain a significant global public health burden. According to the Interna-tional Labour Organization, approximately 340 million occupational accidents and 160 million cases of work-related illness occur annually worldwide [1]. In the United States alone, the Bureau of Labor Statis-tics recorded 5,283 fatal work injuries in 2023, equating to a rate of 3.5 fatalities per 100,000 full-time equivalent workers [2]. The industries carrying the highest risk—

mining, construction, forestry, agricul-ture, and oil and gas—share a common characteristic: their operational environments are frequently remote, physically complex, and inadequately served by standard telecommunications infrastructure.

Effective safety management in these sectors depends critically on communication. The capacity to relay hazard alerts, transmit sensor data, coordinate emergency response, and track lone workers in real time is not merely operationally useful—it can be lifesaving. A systematic literature review by Jamil et al. (2023), spanning nearly 1,500 articles on safety communication in the oil and gas industry, found strong associations between communication effectiveness and both safety compliance and reduction in occupational incidents [3]. Yet in environments where cellular networks are absent or unreliable, conventional communication-dependent safety systems fail at the moment they are needed most.

The emergence of Low-Power Wide-Area Network (LPWAN) technologies, and LoRa (Long Range) radio in particular, has opened new possibilities for deploying monitoring and alerting systems in exactly these challenging environments. LoRa operates in unlicensed ISM radio bands and offers transmission ranges of several kilometres in open terrain with minimal power consumption—properties well-suited to both stationary sensor networks and mobile personnel tracking. A growing body of peer-reviewed research has demonstrated LoRa's feasibility in underground mine monitoring [4, 5, 6], environmental sensing across large outdoor areas [7], and resilient, gateway-free mesh communication [8].

Against this backdrop, Meshtastic—an open-source, firmware-defined peer-to-peer (P2P) mesh network-ing protocol built on LoRa hardware—presents an underexplored opportunity. Meshtastic was first re-leased by Kevin Hester in 2020, originally targeting hobbyist off-grid communication [9]. Its decentralised, self-forming mesh architecture, end-to-end encryption, built-in GPS telemetry, and low-cost commod-ity hardware base distinguish it from prior LoRa-based safety implementations, which typically rely on centralised LoRaWAN gateways. These characteristics could make Meshtastic a particularly attractive candidate for OSH applications in infrastructure-absent environments—but the protocol has not yet been systematically evaluated in this context.

This paper addresses that gap through a literature review and conceptual analysis, as a precursor to the empirical evaluation proposed in Section 6; the source selection method is described in Section 1.1. Section 2 provides a technical overview of the Meshtastic protocol and its underlying hardware ecosys-tem. Section 3 reviews the existing literature on LoRa-based OSH and industrial monitoring applications. Section 4 maps Meshtastic's capabilities against key OSH requirements and proposes concrete use cases. Section 5 critically examines the protocol's limitations and open challenges. Section 6 proposes a framework for empirical evaluation in high-risk industrial settings. Section 7 concludes.

1.1. Method and Scope

This study is a narrative review combining three source types. Peer-reviewed literature was identified through searches of Scopus, IEEE Xplore, and Google Scholar (publication window 2019–2025) using combinations of the terms *LoRa*, *LoRaWAN*, *mesh network*, *Meshtastic*, *mine safety*, *worker safety*, and *occupational safety* ; studies were included if they reported the design or evaluation of LoRa/LPWAN systems in occupational, industrial, or environmental safety contexts. Because Meshtastic itself has, to date, limited peer-reviewed coverage, protocol-level facts are drawn from the official project docu-mentation [9, 10, 11], and vendor-reported deployments are cited as contextual case illustrations only. Scientific claims in this paper rest exclusively on peer-

reviewed sources; technical and vendor documen-tation is used to characterise the technology and its ecosystem, not as scientific evidence.

2. TECHNICAL BACKGROUND

2.1. LoRa Physical Layer

LoRa (Long Range) is a proprietary spread-spectrum modulation technique developed and licensed by Semtech Corporation, operating in unlicensed sub-GHz ISM bands (868 MHz in Europe, 915 MHz in North America). Its chirp spread spectrum (CSS) modulation confers exceptional sensitivity, enabling communication over distances of 2–15 km in open terrain and 1–3 km in urban or obstructed environ-ments, at data rates typically ranging from 0.3 to 27 kbps depending on the spreading factor and band-width configuration [12]. Crucially, LoRa devices operate at extremely low power, enabling battery life measured in years for low-duty-cycle sensing applications [7]. Transmission power levels in the ISM band do not require a radio licence in most jurisdictions, lowering the barrier to deployment significantly.

LoRaWAN, the protocol layer commonly built on top of LoRa, defines a star-of-stars network topol-ogy in which end devices communicate with central gateways, which in turn forward data to a network server. While LoRaWAN is widely deployed in smart city and agricultural monitoring contexts, it requires gateway infrastructure and cannot form ad hoc peer-to-peer networks—a critical limitation in remote, infrastructure-absent environments [13].

2.2. The Meshtastic Protocol

Meshtastic departs from the LoRaWAN paradigm by implementing a fully decentralised, multi-hop mesh network over LoRa. Each device in a Meshtastic network functions as both an end node and a relay, automatically rebroadcasting messages it receives to extend the network's reach across terrain that no single node could cover alone [9]. The protocol supports text messaging, GPS position sharing, and sensor telemetry without requiring any fixed infrastructure—no gateways, no servers, and no internet connectivity.

Meshtastic firmware runs on low-cost commodity hardware development boards based on microcon-trollers such as the ESP32 and nRF52840, combined with LoRa transceiver modules (e.g. Semtech SX1276, SX1262). Complete nodes can be assembled for as little as USD $10–$40, and a growing ecosystem of ready-to-use commercially manufactured devices—including ruggedised, IP-rated trackers—is now available from multiple vendors [14].

Routing in Meshtastic uses a modified flooding algorithm: each packet is assigned a hop counter (max-imum seven hops by default), and every node that receives a novel packet rebroadcasts it until the hop limit is exhausted. This guarantees delivery in sparse networks but introduces scalability constraints in dense deployments; the protocol's developers have reported congestion problems above approximately 50 nodes in the same geographic area, and have developed a specialised event firmware mode support-ing 2,000–2,500 nodes for large gatherings [9].

2.3. Security Architecture

Meshtastic employs AES-256-CTR encryption for the payload of all channel messages transmitted over LoRa, with a distinct pre-shared key (PSK) configurable per channel [10]. Direct messages between nodes are encrypted using Public Key Cryptography (PKC) in firmware versions 2.5.0 and later. The packet header is transmitted unencrypted to allow relay nodes to forward packets they cannot decrypt.

However, several security limitations are relevant to safety-critical deployments: the protocol does not implement Perfect Forward Secrecy (PFS), making it theoretically vulnerable to “harvest now, decrypt later” attacks; node identity authentication is not enforced, making impersonation by a node possessing the channel key trivially possible; and unattended router nodes carrying channel keys can expose those keys if physically compromised [10]. For OSH deployments, these considerations necessitate a security policy that includes regular key rotation, physical security of fixed relay nodes, and evaluation against applicable data protection regulations.

3. RELATED WORK

3.1. Underground Mining

The underground mining sector has been the most active area of LoRa-based safety research. Kumar et al. (2023) developed an Underground Gas Monitoring Device transmitting CH_4, CO, CO_2, O_2, and H_2S concentrations, temperature, and humidity from an underground coal mine model to a surface control system over LoRa, performing reliably in both line-of-sight and non-line-of-sight conditions and triggering alarms on threshold exceedance [4].

Cacciuttolo et al. (2024) reviewed IoT LoRaWAN-based wireless sensor networks for underground mine monitoring within the Industry 4.0 paradigm, identifying real-time continuous data flow, predictive hazard modelling, low-maintenance long-term monitoring, elimination of expensive cabling, and mobile device configuration and visualisation as the primary OSH-relevant advantages [6].

The broader coal mine safety literature also includes LoRa-based worker fall detection and physiolog-ical status monitoring, with one system alerting supervisors via LoRaWAN whenever a miner falls or loses consciousness [5]. These studies collectively validate the physical-layer feasibility of LoRa for mine safety communication but predominantly rely on centralised LoRaWAN architectures requiring fixed gateway installation.

3.2. Construction and Industrial Sites

Beyond mining, LoRaWAN-based worker tracking systems have been piloted in construction and energy sector environments. As a vendor-reported (not independently verified) case, TEKTELIC describes industrial deployments at Moeve’s La Rábida Energy Park providing real-time monitoring of workers, vehicles, and heavy machinery using wearable SEAL trackers featuring fall detection, panic buttons, and SOS alerting [15]. Geofencing capabilities allow automatic alerts when workers enter or leave designated safety zones—a feature directly applicable to construction site safety compliance under ISO 45001. Such deployments illustrate the direction of IoT-LoRa safety systems while remaining dependent on centralised gateway infrastructure.

3.3. Environmental and Forest Monitoring

LoRa mesh networks have also been deployed in large-area environmental sensing relevant to OSH in forestry and outdoor work. Dryad Network's Silvanet system applies LoRa mesh networking to early wildfire detection in forest environments, including a vendor-reported detection of an unauthorised fire in a Lebanese forest in December 2023 [16]. Wu and Liebeherr (2023) demonstrated a self-organising LoRa mesh network (CottonCandy) scalable to hundreds of nodes for large-scale environmental sensing at very low per-node cost, using off-the-shelf components [7].

4. APPLICABILITY OF MESHTASTIC TO OSH

4.1. Mapping Protocol Features to OSH Requirements

Table 1 summarises the alignment between Meshtastic's principal technical characteristics and repre-sentative OSH communication requirements.

The most consequential of these alignments is infrastructure independence: a deployment can be es-tablished in minutes by distributing nodes among workers and fixed relay positions, without prior site preparation—a property particularly valuable in dynamic environments such as disaster response, tem-porary construction sites, or exploration operations. On this foundation, configurable GPS broadcasting supports lone worker protection, geofencing compliance, and search-and-rescue location via a real-time map overlay; small telemetry payloads carry workplace environmental readings without any fixed infrastructure; and SOS alerts propagate across the mesh to supervisors, providing a rapid, low-cost alternative to dedicated personal emergency devices (PEDs) where cellular coverage is absent. AES-256 channel encryption and PKC-secured direct messages address basic confidentiality requirements for personal health and location data, although, as discussed in Section 5, important gaps remain.

Table 1: Meshtastic features mapped to OSH requirements

OSH Requirement	Meshtastic Capability
Infrastructure independence	Fully decentralised; no gateways, servers, or internet required
Personnel tracking	Configurable GPS broadcast; map overlay via mobile/web client
Environmental sensing	Telemetry payloads: temperature, humidity, pressure, air quality
Emergency alerting	Dedicated SOS channel; alerts propagate across all mesh hops
Data confidentiality	AES-256-CTR channel encryption; PKC for direct messages (fw ≥ 2.5.0)
Low deployment cost	Hardware from USD $10–$40 per node; open-source firmware

4.2. Use Case Analysis

Underground and confined space operations. In tunnels, mines, or subsurface construction, Mesh-tastic nodes placed at regular intervals form a self-healing relay chain carrying workers' gas sensor readings and zone-level positions to a surface node—paralleling the LoRaWAN architectures validated in [4, 6], but with no pre-installed infrastructure.

Remote construction, forestry, and fieldwork. Outdoor worksites scattered across large areas with-out cellular coverage present a classic lone worker safety challenge. A Meshtastic mesh composed of workers' personal devices, supplemented by a small number of fixed relay nodes on elevated structures or vehicles, can maintain communication across the site.

Disaster response and post-event rescue. After earthquakes, floods, or wildfires, cellular and Wi-Fi infrastructure is frequently damaged or overwhelmed. Meshtastic is explicitly designed for such sce-narios: nodes form a network autonomously, with no single point of failure, giving OSH professionals coordinating search and rescue a rapidly deployable communications layer; its low barrier to entry has already fostered a broad ecosystem of off-grid deployments on commodity hardware [17].

Industrial hazard monitoring. Fixed nodes equipped with gas, temperature, or dust sensors can form a distributed sensing network across chemical plants, refineries, or waste processing facilities, alerting supervisors to threshold exceedances without permanent network cabling.

4.3. Comparison with Existing Alternatives

Existing commercial alternatives for infrastructure-independent OSH communication include satellite-based personal locator beacons (PLBs), dedicated industrial radio networks (professional and digital mobile radio, PMR/DMR), and proprietary LoRaWAN safety platforms. Satellite PLBs offer global cov-erage but are expensive, unidirectional in most configurations, and provide only coarse-grained location data. Industrial radio networks offer voice communication but generally lack sensor integration, real-time tracking, and encrypted data transmission. Proprietary LoRaWAN safety platforms offer sophisticated features but require gateway installation, ongoing subscription costs, and vendor lock-in. Table 2 sum-marises this comparison across the criteria most relevant to OSH deployment.

Meshtastic occupies a distinct niche: open-source, infrastructure-free, with GPS tracking and sen-sor telemetry at hardware costs one to two orders of magnitude below commercial alternatives; its limitations—discussed below—are real but addressable, and subject to ongoing community improve-ment.

5. LIMITATIONS AND OPEN CHALLENGES

5.1. Bandwidth and Network Scalability

LoRa's low data rate—typically 0.3–5.5 kbps at the spreading factors most commonly used in Meshtastic—imposes strict constraints on the volume and frequency of data that can be transmitted. This is adequate for text messages, GPS coordinates, and short sensor readings, but precludes voice communication, video, or high-frequency sensor streams. In OSH applications requiring continuous physiological mon-itoring (e.g. heart rate, SpO_2) from large numbers of workers, the aggregate bandwidth demand could exceed channel capacity.

Table 2: Meshtastic versus infrastructure-independent OSH communication alternatives (indicative)

Criterion	Meshtastic	Satellite PLB	Industrial PMR/DMR	Proprietary LoRaWAN
On-site infrastructure	None (self-forming)	None (satellites)	Repeaters	Gateways + server
Bidirectional data	Yes	Mostly one-way	Voice-centric	Yes
GPS tracking	Built-in	Coarse	Add-on	Yes
Sensor telemetry	Yes	No	Rare	Yes

Criterion	Meshtastic	Satellite PLB	Industrial PMR/DMR	Proprietary LoRaWAN
Payload encryption	AES-256 (+PKC DMs)	n/a	Varies (often none)	Yes
Scalability	Tens per channel	Per-device (global)	Dozens	Hundreds+
Hardware cost per node	USD $10–40	USD $200–600	USD $200–1000	USD $100–500
Recurring cost	None	Per-activation	Licensing	Subscription
ATEX/ruggedised option	Emerging/limited	Some	Established	Available
Vendor lock-in	None (open source)	Moderate	Moderate	High

Meshtastic's flooding-based routing makes channel airtime, rather than raw node count, the binding con-straint as networks grow. Since firmware version 2.4.0, nodes automatically throttle ancillary telemetry and position traffic once more than 40 nodes are observed within a two-hour window, scaling broadcast intervals upward as channel utilisation rises [11]. Independent measurements of gateway-free LoRa mesh networks report packet delivery ratios of roughly 75–95% depending on the propagation environ-ment, with graceful degradation and recovery under node failure [18, 8]. While the event firmware mode offers further mitigation, these constraints mean Meshtastic is best suited to small-to-medium deploy-ments (teams of up to ~30–40 workers) rather than large industrial facilities with hundreds of personnel.

5.2. Security Limitations

As noted in Section 2.3, Meshtastic's security model has material gaps relative to mission-critical require-ments: without Perfect Forward Secrecy, historical communications could be decrypted if a channel key is later compromised, and without node authentication, sender attribution is not cryptographically guar-anteed and message injection is possible for any entity holding the channel PSK [10]. These limitations may be acceptable where physical access to nodes is controlled and the primary threat is opportunistic radio eavesdropping, but they should be evaluated against site-specific threat assessments, particularly in high-security industrial environments.

5.3. Regulatory Compliance and Data Protection

LoRa transmissions in ISM bands are subject to duty cycle limitations in many jurisdictions (e.g. a maxi-mum 1% duty cycle in the 868 MHz band in Europe under ETSI EN 300 220). The constraint is concrete: at Meshtastic's default European preset (spreading factor 11, 250 kHz bandwidth), a typical position packet occupies on the order of 0.5–0.7 s of airtime, so the 1% limit (36 s of airtime per hour) permits only roughly 50–70 transmissions per node per hour. In dense Meshtastic networks with frequent mes-sage traffic, these limits could be approached or exceeded, particularly on relay nodes, which consume the same airtime budget forwarding messages from multiple sources. OSH practitioners deploying Mesh-tastic must verify local spectrum regulations and configure channel parameters accordingly. In some ju-risdictions, higher-power 1 W LoRa devices are available but require licences or are restricted to specific frequency bands. Hardware placed on the EU market must additionally conform to the Radio Equipment Directive (2014/53/EU).

Worker GPS tracks and physiological telemetry constitute personal data under the GDPR, and their systematic collection amounts to workplace monitoring. Consent is generally not a valid legal basis in the employment relationship, so processing must rest on the employer's legal safety obligations or legitimate interest, with proportionality safeguards such as configurable broadcast

intervals, zone-level rather than precise positioning where sufficient, and defined retention limits; a Data Protection Impact Assessment (Art. 35 GDPR) will typically be required. Notably, because Meshtastic packet headers are transmitted unencrypted (Section 2.3), node identifiers and routing metadata remain observable to third parties even when payloads are encrypted—a residual privacy exposure that deployment policies must take into account.

5.4. Device Robustness and Certifications

Many commercial off-the-shelf Meshtastic hardware platforms are designed for consumer or prosumer use and may not carry the industrial certifications (IP67/68 ingress protection, ATEX/IECEx hazardous atmosphere certification, MIL-SPEC shock and vibration) required for deployment in the most demand-ing OSH environments. Some vendors offer ruggedised enclosures and IP-rated trackers, and ATEX-certified LoRa hardware exists within the broader LoRa ecosystem, but the Meshtastic firmware has not to date been formally validated on ATEX-certified platforms. ATEX certification (and its interna-tional counterpart, IECEx) applies to complete equipment—device, enclosure, battery, and antenna—rather than to firmware, with requirements determined by the zone classification of the deployment area (Zone 0/1/2 for gas atmospheres); the realistic pathway is therefore running Meshtastic firmware on in-trinsically safe (Ex ia) certified LoRa hardware. This gap would need to be addressed before deployment in explosive-atmosphere environments such as gas mines or petrochemical facilities.

5.5. Line-of-Sight Constraints

LoRa performance degrades significantly in non-line-of-sight conditions involving reinforced concrete, dense rock, or metallic barriers common in industrial and underground environments. Multi-hop mesh routing partially compensates by relaying around obstructions, but per-hop range underground is far shorter than in open terrain—as short as 14–17 m in some underground mine testing configurations [4]—so effective underground deployment requires careful relay node placement.

6. PROPOSED FRAMEWORK FOR EMPIRICAL EVALUATION

Given the identified potential and limitations of Meshtastic for OSH applications, we propose a structured three-phase evaluation framework for pilot deployment in a high-risk industrial environment.

Phase 1 — Technical Characterisation. Systematic measurement of network performance (packet delivery ratio, latency, formation time, battery life under OSH-relevant duty cycles) in representative environments—open-air construction sites, underground tunnels, and industrial interiors—compared against baseline LoRaWAN and proprietary systems using standardised protocols.

Phase 2 — Functional Pilot Deployment. Deployment of a Meshtastic-based OSH monitoring system in a controlled field environment, integrating GPS tracking, environmental sensors (gas, temperature, dust), and SOS alerting; evaluation against time-to-alert, position accuracy, false alarm rate, and system availability, with human factors assessment of worker and supervisor acceptance.

Phase 3 — Regulatory and Standards Alignment. Assessment against applicable OSH regulatory requirements (ISO 45001, EU Machinery Directive, local mining regulations) and data protection legisla-tion, with development of a practitioner deployment guide covering hardware selection, security configu-ration, duty cycle management, and maintenance.

7. CONCLUSION

This paper has examined the potential applicability of the Meshtastic open-source LoRa mesh network protocol to occupational safety and health monitoring in environments lacking telecommunications in-frastructure, mapping the protocol's features against core OSH communication requirements; we find compelling grounds for further investigation.

Meshtastic's decentralised, infrastructure-independent architecture, built-in GPS tracking, sensor teleme-try, and very low deployment cost align well with the safety communication needs of high-risk industries in remote or infrastructure-deficient environments; these advantages are partially offset by bandwidth limits in large deployments, an incomplete security model, and the current absence of ATEX certifica-tion.

We conclude that Meshtastic warrants systematic empirical evaluation as a safety communication plat-form and propose a three-phase evaluation framework to this end. In contexts where current alterna-tives are either absent, prohibitively expensive, or insufficiently flexible—including disaster response, remote construction, forestry operations, and small-scale underground works—Meshtastic may repre-sent a genuinely transformative, low-barrier safety technology; future research should prioritise rigorous performance testing, security enhancement, and standards compliance pathways.

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