

Optimizing the Future: Management Innovation

for a Sustainable World

Edited by

Gabriela Proștean

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*Optimizing the Future:
Management Innovation for
a Sustainable World*

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Gabriela Proștean

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Optimizing the Future: Management Innovation for a Sustainable World

Ed. Gabriela Proștean

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INTRODUCTION

Gabriela Proștean

"Optimizing the Future: Managerial Innovation for a Sustainable World" is the theme of this volume, which brings together the studies of the 18th International Management Symposium (SIM 2025). The papers grouped here represent a creative response by engineering and management researchers to the rigor of economic reality, triggered by artificial intelligence and the expanded expression of cutting-edge technologies.

The effort of the authors of this volume has succeeded in harmonizing the theory and practice of specialist professionals and didactic staff from engineering and management universities in Europe and beyond, managing to bring the sustainable needs of organizations closer to the current and spontaneous needs of society, by generating algorithms, methods and theories for the complexity of digital transformation and organizational resilience.

The following chapters discuss organizational challenges, through studies and experiments, determined by academics, doctoral students, and specialists with experience in the fields of engineering and management. The discussions of the results obtained generated innovative solutions, which were the basis for the fusion of interdisciplinary fields, and the breadth of the conclusions highlighted the synergy of the academic environment with the trends of the real economy. It is worth noting contributions that outline innovative entrepreneurship, with the aim of minimizing the gap between the reality of small and medium-sized enterprises and the trends of the European economy. The academic discussions focused on competitiveness based on collaborative models, on the effervescence of emerging technologies, aiming at the configuration of startups based on digitalization and artificial intelligence, on sustainability, on the reduction of operational risks and on the integration of intelligent mechatronic systems in industrial evolution.

A substantial part of the research included in this volume offers practical and complex scenarios, dedicated to sustainability and environmental responsibility in its various manifestations, from ecology and inter-industrial cooperation in the pulp and paper sector to the management and transformation of urban and industrial waste and from circular social entrepreneurship to renewable energy projects carried out in a conflict regime. This research highlights and emphasizes the certainty that economic and social progress, achieved without exhausting natural resources, strongly depends on responsible management, regardless of whether it concerns industrial systems, energy infrastructures or public administration.

The volume also illuminates the challenges in the field of health and safety at work, with selected real studies that focus on reducing risks in construction, fuel storage, car repair services and production environments.

It is worth noting the presence of digital monitoring and management techniques, respectively process management, through the active involvement of cutting-edge technologies, complemented and granted by the human factor, framed in organizational standards. The support of such complex approaches has also attracted studies for the design of educational programs, guarded by leadership in current higher education institutions and physical exercises in office work in the organizational environment, respectively, the role of academic codes of conduct in the formation of ethical leaders in business was highlighted.

Last but not least, several studies address digital inclusion in education or governance, through research on e-voting, seen as a sustainable pillar of digital governance, or knowledge bases, useful for the process of digital self-learning in social management.

In light of these approaches, taken together, the chapters of this volume are presented in a deep scientific manner, which offers a multidimensional perspective on how managerial innovation can generate perspectives of a more sustainable, resilient and equitable future. The editor of this volume would like to thank all authors, reviewers and participants of SIM 2025 for their erudition and dedication, which made possible the harmonious combination of the works of this volume, and hopes that the collected value of these studies will inform both academic research and practical decision-making in the years to come.

BRIDGING THE INNOVATION DIVIDE: APPLIED RESEARCH IN ROMANIAN SMES VERSUS EU TRENDS

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Abstract

Small and Medium-sized Enterprises (SMEs) are pivotal to both economic resilience and innovation across the European Union. Despite representing 99.7% of all enterprises in Romania and employing over 65% of the workforce, Romanian SMEs remain significantly underrepresented in applied research initiatives compared to their Western European counterparts. This paper explores the structural and strategic challenges that hinder research integration within Romanian SMEs, including limited access to funding, weak innovation ecosystems, and insufficient collaboration with academic and technological institutions. Drawing on official data from Eurostat, the European Commission, and the National Institute of Statistics, the study highlights the discrepancy between Romania and the EU average in terms of research participation—particularly within Horizon Europe programs—and proposes actionable strategies to enhance technology transfer and policy alignment. Emphasis is placed on regional disparities, Smart Specialisation Strategies (RIS3), and the role of digitalisation in strengthening SME innovation capacity. The findings underline the urgent need for coherent policy instruments and targeted support to bridge the innovation divide between Romania and the rest of the EU.

Keywords

Small and Medium-sized; Applied Research; Innovation Gap; EU Funding; Romania vs EU Comparison.

I. Introduction

Small and Medium-sized Enterprises (SMEs) are the cornerstone of economic growth, innovation, and employment in the European Union. Accounting for over

99% of all businesses and generating more than half of the value added in the EU economy, SMEs play a central role in fostering competitiveness and technological progress. Their flexibility, adaptability, and proximity to market needs make them ideal vectors for applying research and development (R&D) outcomes.

In Romania, SMEs mirror the European structural composition, representing 99.7% of all active firms and contributing approximately 49–50% to the national GDP. However, their involvement in applied research remains limited and fragmented. Recent data from the European Commission shows that only 0.7% of Romanian SMEs have participated in Horizon Europe programs, far below the EU average of 3.5%. This discrepancy reveals not only a research gap but also an innovation divide that risks deepening socio-economic disparities between Romania and more research-intensive EU member states.

Several factors contribute to this divergence. Romanian SMEs often face systemic barriers such as inadequate access to funding, a lack of skilled personnel, limited digital infrastructure, and insufficient collaboration with research institutions and innovation clusters. Moreover, the fragmentation of regional innovation ecosystems and the absence of long-term innovation strategies at the firm level further hinder the integration of R&D into business models.

The aim of this paper is to provide a comparative analysis of applied research participation among SMEs in Romania and the broader EU context. We explore the institutional, financial, and structural constraints specific to the Romanian environment, while highlighting successful policy frameworks and strategic partnerships implemented elsewhere in Europe. Special attention is given to the role of Smart Specialisation Strategies (RIS3), digitalisation trends, and technology transfer mechanisms as enablers of SME-driven innovation.

By investigating both challenges and opportunities, this study contributes to a more nuanced understanding of the research-to-innovation continuum in SMEs and offers evidence-based recommendations for policymakers, innovation intermediaries, and business leaders.

II. Methodology

This study employs a mixed-methods research design, integrating both quantitative and qualitative approaches to explore the extent to which Romanian SMEs engage in applied research and how this compares with EU-level performance.

A. Data Sources and Collection

Quantitative data were collected from several authoritative sources, including:

- Eurostat – Structural Business Statistics, which provides key SME indicators on employment, value added, and innovation output [1];

- European Commission – Annual Report on European SMEs 2022/2023, offering insights on SME participation in research, access to funding, and innovation intensity [2];
- Romanian National Institute of Statistics (INS), for updated figures regarding the number, size, and economic contribution of SMEs across sectors [3];
- Digital Economy and Society Index (DESI), used to assess digital capabilities of SMEs across EU countries [4];
- Public datasets from Horizon Europe and COSME programme dashboards, indicating Romania's participation rate in EU-funded research projects [5].

In addition, qualitative data were sourced from Romanian and European policy documents, including regional innovation strategies (RIS3), national research frameworks, and strategic development plans [6].

B. Analytical Framework

The research follows a comparative-descriptive approach based on two analytical axes:

- Participation Metrics – Assessing SMEs' engagement in research projects, collaboration with universities, involvement in clusters, and application to EU or national funding schemes [7].
- Enabling Conditions and Barriers – Evaluating structural factors such as financial access, digitalisation, human capital, and regional support ecosystems [8].

Benchmarking was conducted using KPIs such as:

- SME R&D expenditure as % of turnover [9].
- Participation in Horizon Europe and COSME (% of total SMEs) [5].
- Level of cooperation with academia and innovation clusters [10].
- DESI digitalisation scores for SMEs [4].
- Share of innovative products or services introduced in the last 3 years [2].

The analysis compared Romania's position relative to the EU average and selected high-performing countries (e.g., Germany, Finland, Netherlands) [1][2].

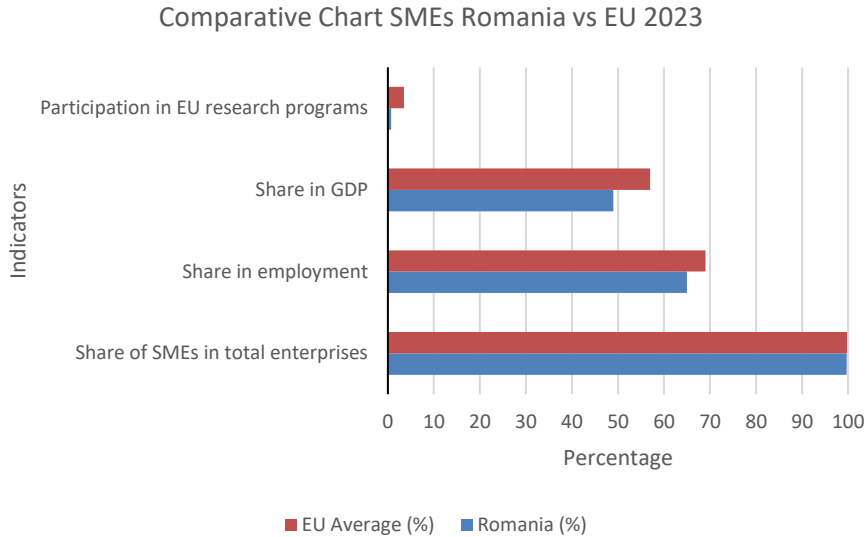


Figure 1. Comparative Chart SMEs Romania vs EU 2023

Table 1. The table below presents a comparative overview of key performance indicators for small and medium-sized enterprises (SMEs) in Romania and the European Union average in 2023.

Indicator	Romania (2023)	EU Average (2023)
SMEs as % of total enterprises	99.7%	99.8%
SMEs employment contribution	65–67%	67–70%
SMEs GDP contribution	49%	56–58%

C. Regional Case Analysis

To capture the intra-national dimension, a regional comparative lens was applied by examining three development regions in Romania with distinct RIS3 priorities:

- North-East: Focused on bioeconomy and agro-innovation [6];
- South-East: Prioritising blue economy and renewable energy [6];
- Centre Region: Targeting mechatronics and creative industries [6].

These cases highlight how localized policies shape SME participation in research and access to funds and help identify both success factors and systemic bottlenecks.

D. Regional Case Analysis

This study uses the most up-to-date available data (2022–2023), but several limitations apply. First, data comparability between EU member states can be affected by differences in reporting cycles or indicators [1][5]. Second, SME involvement in applied research may be underrepresented in national statistics due to delayed or underreported figures [3].

Despite these, the use of triangulation across multiple sources strengthens the reliability of the results, while the combination of macro- and micro-level analyses ensures a robust understanding of SME research engagement.

E. Research Objective and Scope

The primary objective of this research is to investigate the current state, challenges, and opportunities related to the implementation of applied research projects within small and medium-sized enterprises (SMEs), with a particular focus on Romania, while maintaining a broader comparative perspective with the European Union. This study aims to identify structural barriers, assess the effectiveness of public policies and funding instruments, and evaluate the role of SMEs in fostering innovation ecosystems at both national and regional levels.

Specifically, the research seeks to:

- Analyse the economic and strategic relevance of SMEs in Romania and the EU.
- Assess the degree of integration of applied research in Romanian SMEs.
- Identify funding mechanisms (EU and national) that support research-driven innovation in SMEs.
- Evaluate the impact of digitalization and technological readiness on SME research capacity.
- Examine the collaboration frameworks between SMEs, universities, and innovation clusters.
- Propose recommendations for improving the absorption and efficiency of research initiatives in SMEs.

The scope of this research covers:

- SMEs as defined by EU Recommendation 2003/361/EC, focusing on enterprises with fewer than 250 employees and an annual turnover of less than €50 million.
- The period between 2015 and 2024, corresponding to relevant EU funding cycles and digital transformation trends.
- Quantitative indicators (e.g., SME share of GDP, employment, participation in Horizon Europe) and qualitative aspects (e.g., innovation culture, strategic planning for R&D).
- Comparative regional analysis across Romanian development regions and selected EU countries with similar economic profiles.

By delineating these objectives and boundaries, the research aims to contribute both theoretically and practically to understanding how SMEs can better engage in applied research, leveraging innovation as a competitive advantage.

III. Results

The results of the research indicate that Romanian small and medium-sized enterprises (SMEs) continue to play a significant structural role in the national economy, yet they encounter considerable obstacles when engaging in research and innovation activities. Empirical data from Eurostat and national statistics show that SMEs account for 99.7% of all active enterprises in Romania, employ over 65% of the national workforce, and contribute approximately 49–50% to the country's gross domestic product (GDP). While these figures reflect a robust presence of SMEs in economic terms, their performance in accessing and leveraging research funding remains substantially limited.

At the European level, the average participation rate of SMEs in Horizon Europe research funding programs reached 3.5% in 2023. By contrast, only 0.7% of Romanian SMEs were involved in such initiatives. This striking gap reveals structural deficiencies in terms of institutional support, digital infrastructure, and research readiness across the Romanian SME landscape. The data suggests that many firms lack the internal capacity and strategic orientation required to access these competitive funding instruments. Despite numerous national programs supporting entrepreneurship and innovation, such as Start-Up Nation and POCU, the absorption rate of research-oriented funding in Romania remains modest and uneven across sectors and regions.

A further examination of sectoral investment patterns reveals that European research and innovation funds allocated to Romanian SMEs between 2014 and 2020 were concentrated predominantly in a few key areas. The most targeted sectors included information and communication technology, agro-food innovation, renewable energy, health sciences, and manufacturing technologies such as mechatronics. Although these investments reflect alignment with EU research priorities, the actual impact on innovation outputs within SMEs appears limited, largely due to insufficient follow-up mechanisms, weak commercialization channels, and low institutional connectivity.

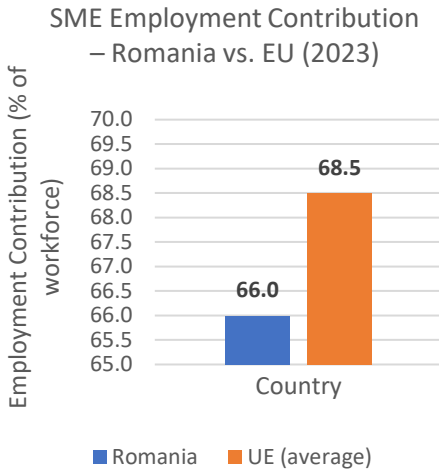


Figure 2. SME Employment Contribution Romania vs. EU (2023)

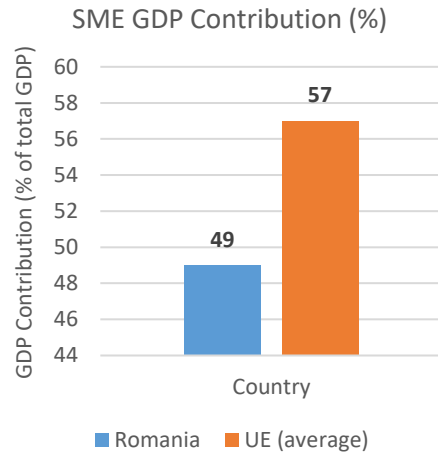


Figure 3. SME GDP Contribution Romania vs. EU (2023)

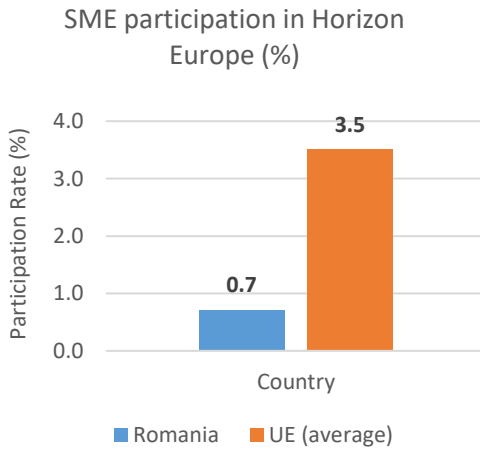


Figure 4. SME Participation in Horizon Europe Romania vs. EU (2023)

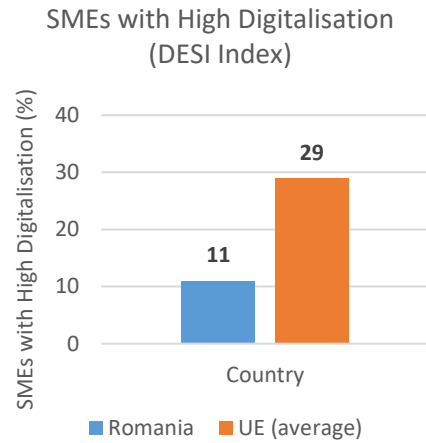


Figure 5. SMEs with High Digitalisation Romania vs. EU (2023)

In terms of digital maturity, Romanian SMEs rank significantly below the European average. According to the Digital Economy and Society Index (DESI), only around 11% of SMEs in Romania had a high level of digitalization between 2015 and 2020, compared to 29% across the EU. This technological lag correlates

strongly with diminished research performance and the adoption of innovation. Digital tools are fundamental enablers of participation in research projects, especially in cross-border collaborations, where interoperability and data access are essential. The limited integration of digital infrastructure within Romanian SMEs thus acts as a barrier to research participation, both in terms of execution and in accessing funding mechanisms that require a minimum level of technological capability.

Regional disparities are also evident in the implementation of Smart Specialisation Strategies (RIS3), a key component of EU cohesion policy. Romanian development regions have defined distinct priority sectors based on their local potential and economic fabric. For instance, the North-East region has prioritized bioeconomy and agro-innovation, the South-East has focused on renewable energy and maritime industries, while the Centre region emphasizes creative industries and advanced manufacturing. While RIS3 frameworks are meant to tailor research priorities to regional strengths, the capacity of SMEs to actively participate in these strategies remains limited by a lack of coordination between regional governance bodies, academic institutions, and the business environment.

Ultimately, the evidence points to several persistent bottlenecks that hinder Romanian SMEs' integration of applied research into their business models. These include a shortage of qualified personnel in research and development, limited access to strategic consultancy services, inadequate communication between academia and the private sector, and a general lack of awareness regarding funding instruments and their requirements. Addressing these limitations requires not only increased financial resources but also a shift in institutional design, capacity-building, and improved outreach mechanisms to ensure inclusivity and long-term engagement.

IV. Conclusion

This study sheds light on the critical role of SMEs in shaping Romania's economic resilience and innovation potential, particularly in contrast with broader European Union trends. Although Romanian SMEs constitute the majority of enterprises and serve as key drivers of employment, their contribution to research, innovation, and productivity remains below their potential. The comparative analysis with EU data reveals persistent structural and operational gaps, particularly in digitalization, access to funding, and participation in European research programs.

The findings point to a need for systemic change at multiple levels. First, enhancing SMEs' digital capabilities is essential. Low digital maturity significantly hampers the ability of firms to engage in research collaboration, adopt new technologies, and integrate innovation into business models. Addressing this issue requires not only investment in infrastructure but also in education and digital literacy across the SME workforce.

Second, the integration of SMEs into research ecosystems remains fragmented. Despite initiatives such as Horizon Europe and RIS3 strategies, Romanian SMEs' actual participation in collaborative innovation remains minimal. Strengthening partnerships between universities, research institutes, and the private sector is essential to creating a functional innovation ecosystem. Furthermore, the promotion of intermediary organizations such as innovation clusters and technology transfer centers could significantly ease the transition from academic knowledge to market-ready solutions.

Third, regional disparities must be acknowledged and addressed. While smart specialization strategies reflect regional strengths and priorities, their implementation varies widely across Romanian territories. Ensuring consistency, equity, and effectiveness in the distribution of research and innovation funds is key to fostering balanced regional development and unlocking the untapped potential of SMEs in less-developed areas.

Ultimately, the research highlights both the urgency and the opportunity of strengthening SME participation in applied research. Policymakers, academic institutions, and business leaders must work together to create a more enabling environment for innovation—one where SMEs are not peripheral actors but central drivers of sustainable growth. Supporting their capacity to innovate is not only a matter of economic competitiveness but also a strategic imperative for ensuring Romania's successful integration into a knowledge-based European economy. At the same time, these findings underline the need for further investigation into regional specificities, digitalisation trends, and collaborative mechanisms, aspects which are outlined in the following section on future research directions.

V. Future Research Directions

While the present paper has explored the current state of applied research in Romanian SMEs compared to EU trends, further work is needed to provide a more comprehensive understanding of the phenomenon. Several directions for future research can be outlined:

- **Extend longitudinal analysis (2025–2030):** Future studies should cover longer time horizons, integrating upcoming data from Horizon Europe and Romania's National Recovery and Resilience Plan (PNRR), to capture structural changes in SME research involvement.
- **Regional case studies:** In-depth investigations of SMEs across Romanian regions (e.g., North-East, Centre, South-East) could provide insights into territorial disparities and highlight localized barriers to research participation.
- **Digitalisation and Industry 4.0 adoption:** Further research should explore the extent to which advanced digital tools, artificial intelligence, and Industry 4.0 technologies shape SME innovation capacity and competitiveness.

- Collaborative ecosystems: Future work could examine the impact of clusters, technological transfer centres, and cross-border partnerships on bridging the innovation divide between Romania and the EU average.

- Socio-economic impact assessment: It would also be valuable to assess how increased SME participation in research contributes to Romania's economic growth, resilience, and convergence with EU development standards.

By pursuing these avenues, research can support policymakers and business leaders in designing targeted measures that enhance the role of SMEs in innovation-driven growth.

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DESIGNING LEADERSHIP PROGRAMMES IN HIGHER EDUCATION: THE CASE STUDIES OF MOROCCO AND KOSOVO & ALBANIA

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Abstract

The global demand for effective and culturally relevant leadership in higher education is increasing, particularly in regions undergoing reform and structural transformation. This study analyses two Erasmus+ Capacity Building in Higher Education (CBHE) initiatives — project MORHEL for Morocco and project LEADALKO for Albania and Kosovo — emphasising leadership development through modular, evidence-based, and interactive programming. This study evaluates critical design aspects, implementation challenges, and context-specific dynamics using the Higher Education Leadership Qualities and Skills (HELQS) framework, project documentation, and assessment data. The results underscore the crucial importance of competency-based training, a cohesive infrastructure, and policy coherence for sustained leadership development. The cross-case research validates the adaptability of HELQS across geopolitical contexts and underscores the necessity for national coordination and institutional ownership. The article advances the theoretical discourse on transformative and distributed leadership within higher education, providing pragmatic insights for future capacity-building initiatives. The LEADALKO instance focuses on needs analysis and program design, whereas the MORHEL case emphasises the piloting phase of implementation.

Keywords

Leadership in higher education; Erasmus+ CBHE; HELQS framework; MORHEL project; LEADALKO project; national leadership development; Quality Education; Strong Institutions and Partnerships for the Goals

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I. Introduction: Framing Leadership for Transformative Change in Higher Education

In the evolving landscape of higher education, leadership has emerged as a critical element for institutional resilience, strategic transformation, and societal impact. As higher education systems face escalating pressures to internationalise, improve quality, and align with socioeconomic needs, the development of leadership capacity has become a strategic imperative (Middlehurst, 2004; Bolden, Petrov, & Gosling, 2009). Contemporary leadership transcends mere administrative skills and necessitates the ability to guide organisations through uncertainty, change, and innovation (Khan, 2017).

Within the global policy context, the United Nations Sustainable Development Goals (SDGs) underscore this necessity — especially SDG 4 (Quality Education), SDG 16 (Peace, Justice and Strong Institutions), and SDG 17 (Partnerships for the Goals). Enhancing leadership in higher education directly promotes SDG 4 by elevating the quality of teaching and learning, bolsters SDG 16 through the establishment of transparent and accountable governance, and aids SDG 17 by cultivating enduring, cross-border collaborations among higher education institutions (HEIs).

The scholarly landscape offers various theoretical viewpoints, each serving unique explanatory purposes. Initial trait theories suggested that leadership was contingent upon innate attributes; however, these theories faced criticism for overlooking contextual influences (Zaccaro, 2007; Salihu, 2019). Behavioural theories analysed leadership actions—task-oriented, relational, or change-driven—whereas situational and contingency theories emphasised aligning leadership styles with environmental contexts (Gümüş et al., 2018; Hersey et al., 1982; Amanchukwu et al., 2015). Conventional theories often lack the sophistication needed to address the complex realities of higher education institutions, particularly in post-socialist or post-colonial contexts (Muftahu, 2019).

Contemporary frameworks favour distributed, transformational, instructional, and adaptable leadership paradigms. These emphasise collaboration, shared governance, and organisational flexibility in response to change. Transformational leadership (Bass & Avolio, 1994) emphasises vision and organisational culture; distributed leadership fosters collective agency; and authentic leadership prioritises ethical behaviour and self-awareness (Avolio & Gardner, 2005; Spillane, 2006).

These models align with a "leadership-as-practice" perspective, which characterises leadership as a relational and emergent effort rather than a consequence of formal power. Competency-based approaches, such as the HELQS model, encapsulate these theoretical shifts by integrating strategic, operational, and personal development domains. Leadership development is increasingly informed by diagnostic tools, such as 360-degree feedback, which promote reflective practice and continuous improvement (Atwater & Waldman, 1998; Nowack & Mashihi, 2012). Furthermore, systems thinking perspectives (Senge, 1990; Oakland, 2001) emphasise that effective leaders should influence institutional ecosystems rather than solely oversee individuals.

This change in leadership philosophy signals broader developments in higher education governance, characterised by decentralisation, digital progress, and increased demands for accountability, inclusion, and societal relevance. Muftahu (2019) asserts that effective leadership in this setting requires contextual knowledge, adaptability, and an ethical foundation—qualities often overlooked by conventional models.

The MORHEL and LEADALCO project-based programs offer valuable insights into the implementation of contemporary leadership paradigms. These CBHE programs incorporate modular, evidence-based training into national reform plans, demonstrating how transformational and participative leadership may facilitate institutional change across various geopolitical and cultural contexts. These two cases extend the legacy of previous international E+ capacity-building projects on leadership, conducted in the last 5 years, such as iHiLEAD in Indonesia, and MHELM in Moldova—into the Western Balkans and in Morocco. These cases demonstrate that by openly linking their objectives and outcomes to SDG 4, SDG 16, and SDG 17, leadership development can simultaneously address national reform agendas and advance global sustainable development goals.

II. MORHEL: Leadership Development in the Moroccan Higher Education Sector

The Moroccan Higher Education Leadership (MORHEL) project is a nationally coordinated initiative under the Erasmus+ framework, aiming to enhance leadership and governance skills in Moroccan higher education institutions (HEIs).

The project's core objective is to create a National Leadership Development Programme (NLDP), delivered through a network of National Leadership Development Centres (NLDCs), to institutionalise leadership training and drive systemic, sustainable improvement in higher education leadership practices (MORHEL 2023).

The NLDP was carefully designed through a competency-based, needs-driven methodology. It is based on a diagnostic examination of 12 Moroccan higher education institutions and a comparison with European best practices. It focuses on five principal leadership profiles: university presidents, senior strategic managers,

academic leaders, functional heads, and administrative managers. National research undertaken in 2021–2022 revealed substantial developmental gaps in effect management, internationalisation, finance, change, and people performance—areas that now underpin the NLDP's modular training structure. Four principal thematic elements constitute its structural framework: Leading Strategy & Governance, Leading Operations & Systems, Leading People & Change, and a Higher Education Change Project. The training consists of 12 modules (MORHEL 2023).

The pilot cohort, implemented in 2/2 of 2024, delivered all 12 modules to 22 participants from 11 Moroccan HEIs, utilising both face-to-face and online modalities. Sessions utilised interactive methodologies—SWOT analyses, case studies, simulations, and live polling technologies (e.g., Mentimeter)—to promote peer learning and experiential reflection. This approach enabled peer-to-peer learning and fostered cross-institutional networks, which is a primary purpose of the program. The "Change Project" component was directed by foreign experts. Participants formulated institutional-level initiatives designed to achieve quantifiable organisational enhancements in accordance with national aims. Coaching focused on delivering actionable results, stakeholder consensus, and practicality within institutional contexts. Deliverables comprised case reports and final presentations, reinforcing the application of leadership skills to real-world higher education challenges (MORHEL, 2024).

Quantitative and qualitative evaluations from 2024 confirmed the pilot's effectiveness. Participants reported substantial knowledge acquisition (mean score, 4.6/5) and improvements in leadership skills (4.5/5). Instructors emphasised participant motivation and the effectiveness of the strategies introduced to address practical governance challenges (MORHEL 2024).

Nonetheless, several operational and pedagogical constraints arose. The quality and usability of pre-session preparation materials received a low rating (1.6/5), while instructor notes were deemed insufficiently detailed (2.2/5), compromising replicability. Participation in online sessions declined over time, largely due to scheduling conflicts and session fatigue. Intensive modules, such as Finance, caused cognitive overload, while others, such as Human Resources, required a broader range of activities to maintain engagement. Moreover, certain modules exhibited overlapping content, reducing overall efficiency and clarity (MORHEL 2024).

The project team has provided strong recommendations, including reorganising courses into concise, thematic blocks, improving instructor guidance resources, introducing optional online assignments, and creating a nationally recognised certification pathway.

Enhancements have been evaluated, and the program has been refined for implementation in 2025. In 2025, the subsequent four cohorts of participants will participate in the program, totalling approximately 80 individuals in training that year. Results on implementation are not yet available.

The Ministry of Higher Education plays a pivotal role in institutionalising the program through policy integration, financial assurances, and oversight of NLDC development (MORHEL 2023).

The primary objective of MORHEL is to establish NLDCs at every university – regional centres that can customise leadership development to local conditions while maintaining alignment with national reform objectives. These centres are anticipated to provide continuous training, consultancy, and stakeholder engagement, thus embedding leadership development within university infrastructure (MORHEL 2024a). This approach emulates successful models from EU counterparts and aligns with findings from comparative foresight initiatives, underscoring the significance of cohesive, contextually aware leadership development frameworks (Andreescu et al., 2012).

The MORHEL project is a flagship initiative that integrates capacity building, policy coherence, and institutional innovation to further Morocco's higher education reform objectives. Embedding leadership development inside institutional structures and national frameworks offers a replicable model for other post-reform systems worldwide.

III. LEADALKO: Leadership Capacity Building in Albania and Kosovo

The LEADALKO project addresses critical leadership gaps in the higher education sectors of Albania and Kosovo, nations undergoing systemic transition with limited prior investment in leadership development. The project entails a thorough investigation and a methodical evaluation of requirements, uncovering a notable lack of leadership. Notwithstanding heightened policy emphasis on enhancing governance, quality, and internationalisation in higher education (Eurydice, 2023; Osmani, 2022), both Albania and Kosovo lack established frameworks for cultivating leadership competencies, which continues to hinder sustainable reform implementation.

A study conducted in late 2023 with 157 leaders from 10 higher education institutions in Albania and Kosovo revealed that 39% of participants had not received prior leadership development opportunities, and just 13% had access to a formal curriculum. The remaining opportunities were fragmented, mainly consisting of networking gatherings or short training sessions. Nevertheless, demand remains robust: 92% of respondents expressed interest in a formal, accredited program that includes elements such as networking (53%), coaching (48%), and development seminars (46%) (LEADALKO 2025b).

The study employed the Higher Education Leadership Qualities and Skills (HELQS) framework to evaluate 13 categories of leadership proficiency. The analysis identified four domains as primary development priorities: resource management, impact leadership (including policy and economic involvement), leadership in equality, diversity, and inclusion (EDI), and leadership in

internationalisation. The domains exhibited the lowest average self-assessment scores, suggesting that leaders in these areas recognise substantial developmental need in systemic and strategic competencies. In contrast, personal domains such as personal values, personal productivity, and interpersonal impact received the highest scores, consistent with trends observed in comparable contexts of E+ capacity-building projects on leadership such as Moldova (E+ project Mhelm), Indonesia (E+ project iHiLEAD), and Morocco (E+ project MORHEL).

An in-depth analysis of individual talents indicated that the least-rated abilities encompassed influencing governmental policy, financial management, risk assessment, project oversight, economic development advocacy, and operational management. The findings indicate that numerous higher education leaders in Albania and Kosovo, frequently selected for their academic qualifications rather than administrative expertise, perceive themselves as inadequately equipped for strategic leadership positions. In contrast, respondents indicated elevated levels of intrinsic motivation, integrity, and interpersonal effectiveness, suggesting strong foundational values and a capacity for growth (LEADALKO, 2025b).

Furthermore, conversations with senior institutional executives confirmed that leadership roles are frequently assigned primarily on the basis of academic credentials rather than managerial competencies—a pattern that the project seeks to rectify (LEADALKO 2025b).

The 2023 study also examined the impact of demographic variables on leadership self-evaluations. Leaders from Kosovo typically assessed their performance more favourably across many dimensions compared to their Albanian counterparts, despite a robust correlation ($\rho = 0.95$) suggesting common developmental aims. Age showed a positive correlation with self-assessments of leadership across almost all categories, suggesting that confidence increases with experience. Conversely, variables such as gender, tenure, and work position exhibited less explanatory capacity, indicating the necessity for comprehensive, inclusive development strategies across various roles and demographics (LEADALKO, 2025b).

Additional qualitative observations were obtained via interviews conducted in early 2025 with 15 senior leaders, comprising rectors, vice-rectors, ministry officials, and quality assurance specialists. Interviewees recognised a range of interrelated leadership issues, including brain drain from migration, declining student enrolment, obstacles to staff recruitment and retention, financial instability within institutions, and regulatory rigidity. A persistent topic was the disjunction between higher education offerings and national development aspirations, especially in aligning curricula with labour market demands and significantly contributing to socio-economic advancement. These challenges require leaders who are not only technically proficient but also adaptable, strategically oriented, and system-aware (LEADALKO, 2025b).

In addition to challenges, the findings also highlighted existing leadership among respondents, including significant affective (intrinsic) and instrumental

(career-oriented) desire for professional development, a pronounced orientation towards innovation, and robust ethical principles. Affective commitment to learning was the most significant predictor of leadership competency, exhibiting a statistically significant correlation with nearly all HELQS dimensions. Action-oriented participation in leadership development demonstrated significant correlations, whilst organisational support exhibited a moderate influence. In contrast, instrumental drive and open-mindedness served as less robust predictors (LEADALKO, 2025b).

Based on these findings, the LEADALKO project is instituting a National Leadership Development Programme (NLDP) and a network of National Leadership Development Centres (NLDCs) across Albania and Kosovo. The program is customised to local conditions while being guided by European best practices. It focuses on five leadership profiles: university presidents, senior executives, strategic leaders, directors of academic programs, and administrative managers. The program design is modular, including workshops, coaching, 360-degree feedback, and institutional change initiatives. It emphasises action learning and peer collaboration among institutions, cultivating networks that facilitate both institutional and sectoral transformation (LEADALKO, 2025a; 2025b).

IV. Cross-Case Insights and Theoretical Integration

MORHEL and LEADALKO exemplify the significance of participative, reflective, and contextually integrated leadership development that directly advances the Sustainable Development Goals (SDGs). Both initiatives implement SDG 4 by enhancing educational quality through organised leadership training; SDG 16 by establishing transparent, accountable, and responsive governance systems; and SDG 17 by reinforcing national, regional, and international collaboration among higher education institutions.

Despite variations in governance traditions—Morocco’s nationally coordinated, policy-oriented model contrasted with the Western Balkans’ diagnostic-driven, grassroots methodology—both initiatives illustrate that leadership capacity development can be tailored to diverse political, cultural, and institutional contexts. The comparative research highlights that frameworks such as HELQS are adaptable across geopolitical contexts when tailored to local requirements, rendering them useful models for other nations undertaking transformation.

From a theoretical perspective, both projects exemplify systems-thinking methodologies that emphasise institutional ecosystems rather than individual charisma (Black, 2015; Seddon, 2003), illustrating that leadership development aligned with the SDGs is contextually sensitive and internationally relevant.

V. Conclusion

The cultivation of effective leadership in higher education is essential for fostering institutional resilience, innovation, and transformation. This paper demonstrates that modular, evidence-based leadership programs when embedded within national policy frameworks, possess significant potential to strengthen institutional governance and academic cultures, as evidenced by the case studies of the MORHEL and LEADALKO projects. These outcomes reinforce SDG 4, SDG 16, and SDG 17 by enhancing education quality, strengthening governance, and cultivating lasting partnerships.

The MORHEL project in Morocco has produced evaluative evidence indicating the effectiveness of competency-based, participatory leadership training in enhancing individual skills and institutional networking. LEADALKO, now in its preliminary implementation phase, presents a comprehensive framework for scalable leadership development tailored to the evolving institutional contexts of Albania and Kosovo. Both projects demonstrate how leadership development, aligned with national reform agendas and the SDGs, may serve as a strategic catalyst for extensive educational transformation with both national and global significance.

This study highlights the relevance of contemporary leadership models—namely, distributed, transformational, and adaptive leadership—as more effective alternatives to traditional hierarchical or command-driven models (Gümüç et al., 2018; Black, 2015; Dube et al., 2022). In the context of higher education institutions (HEIs) operating within intricate, globalised, and resource-constrained settings, effective leadership necessitates strategic management, emotional intelligence, ethical commitment, systems thinking, and proficiency in managing change and uncertainty (McCaffery, 2019; Amanchukwu et al., 2015).

Moreover, leadership development should be understood not as an intermittent intervention, but as a continuous, reflective, and adaptive process that evolves in response to institutional needs and the sociopolitical environment (Muftahu, 2019; Dongare & Namdeo, 2023). Embedding such development into institutional infrastructure—through leadership centres, peer networks, and policy frameworks—ensures both sustainability and ongoing alignment with the SDGs.

Several imperatives emerge moving forward:

- Firstly, institutional leadership frameworks must adopt flexible, context-specific
- approaches that recognise national and institutional diversity.
- Secondly, program design should prioritise experiential learning, coaching, and peer support over purely didactic methods.
- Evaluation strategies must encompass not only satisfaction metrics but also assess long-term behavioural and institutional impact, including contributions to SDG targets.

- National authorities should act not only as funders, but also as coordinators and guarantors of coherence, quality, and strategic alignment.

Investing in leadership development is fundamental to building higher education institutions that are adaptative, inclusive, and proficient in functioning as catalysts for knowledge, democracy, and social justice, while furthering the overarching goals of the 2030 Agenda for Sustainable Development.

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EXPLAINING INNOVATION ADOPTION IN DIGITAL AND SUSTAINABLE CONTEXTS: A LITERATURE-BASED PERSPECTIVE

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Abstract

Abstract: This work presents a comparative literature assessment of four principal theories of innovation adoption: the Technology Acceptance Model (TAM), the Theory of Planned Behaviour (TPB), the Diffusion of Innovations (DOI), and the Unified Theory of Acceptance and Use of Technology (UTAUT). Their explanatory capacity is examined within the framework of digital transformation and sustainability-oriented advances, specifically in the context of electric truck mobility. Research suggests that although each model possesses distinct advantages, integrative strategies are essential to encompass technical, behavioural, systemic, and environmental factors influencing adoption. The study enhances theoretical understanding by delineating complementarities across models and informs practice by elucidating avenues for sustainable innovation management.

Keywords

innovation adoption, TAM, TPB, DOI, UTAUT, sustainability, digital transformation, electric mobility.

I. Introduction

The swift advancement of digital technology and the worldwide need for sustainability have transformed how organisations and communities see innovation. Digital transformation has emerged as a pivotal factor in organisational competitiveness, whilst sustainable practices are widely regarded as vital for enduring development and resilience. As industries transition to low-carbon

economies and digital ecosystems, the adoption of innovations has become essential for future optimisation.

Research on innovation adoption has garnered considerable attention across several disciplines, including information systems, marketing, and environmental management. A significant problem is elucidating the reasons for individuals, organisations, and societies adopting or resisting new technologies, particularly when such advances require behavioural, cultural, and organisational transformations. In recent decades, numerous theoretical models have been formulated to elucidate the factors influencing adoption, with the Technology Acceptance Model (TAM) [1], the Theory of Planned Behaviour (TPB) [2], the Diffusion of Innovations theory (DOI) [3], and the Unified Theory of Acceptance and Use of Technology (UTAUT) [4] being the most prevalently utilised.

These models have undergone rigorous testing across domains such as information systems, e-commerce, mobile apps, and, more recently, in sustainable breakthroughs such as electric mobility, renewable energy technologies, and digital platforms for green logistics [5]–[7]. Nevertheless, the evidence is fragmented: each model emphasises distinct explanatory aspects, exhibiting differing levels of predictive efficacy across situations. The Technology Acceptance Model (TAM) highlights perceived utility and ease of use, whereas the Theory of Planned Behaviour (TPB) focuses on attitudes, subjective norms, and perceived behavioural control. DOI emphasises the attributes of innovations and their dissemination within social systems, whereas UTAUT consolidates several predictors into performance expectancy, effort expectancy, social impact, and enabling factors.

Comprehending the synergies and constraints of these frameworks is crucial for academics and professionals seeking to enhance innovation management in a sustainable context. This article rigorously compares the models, emphasising their strengths, shortcomings, and relevance in digital and sustainability-oriented situations. The contribution is twofold: first, to offer a literature-based view on the explanatory power of adoption models; second, to delineate integrative insights for management innovation strategies matched with sustainability objectives.

II. Literature review

A. Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM), initially proposed by Davis in 1986 and subsequently formalised by Davis, Bagozzi, and Warshaw in 1989, is a prominent paradigm for forecasting technology uptake. The fundamental premise is that two primary factors—Perceived Usefulness (PU) and Perceived Ease of Use (PEOU)—shape consumers' perceptions towards a technology, therefore affecting their behavioural intention and actual utilisation.

Over time, the Technology Acceptance Model (TAM) has been expanded and enhanced, resulting in TAM2 and TAM3, which include social impact and enabling factors [3]. Additionally, scholars have integrated the Technology Acceptance Model (TAM) with supplementary frameworks, such as the Theory of Planned Behaviour (TPB) and the Unified Theory of Acceptance and Use of Technology (UTAUT), to enhance its explanatory capacity across many settings [4].

Recent research has utilised the Technology Acceptance Model (TAM) in the contexts of digitalisation and sustainability initiatives. Ajina (2024) amalgamated the Technology Acceptance Model with the Innovation Resistance Theory to elucidate green IT adoption, highlighting the interplay between environmental concerns and perceived utility [5]. Anser et al. (2020) introduced the Energy-Augmented Technology Acceptance Model (EA-TAM), emphasising the significance of energy efficiency perceptions in green logistics and corporate sustainability [6]. Schorr (2023) conducted a thorough assessment of the Technology Acceptance Model (TAM) applications in digital transformation research, affirming its significance as a resilient and flexible framework [7].

In sustainability contexts, the Technology Acceptance Model (TAM) has been particularly successful in examining the uptake of electric vehicles, renewable energy systems, and digital platforms for sustainable consumption. Nonetheless, a primary critique is its narrow emphasis on external variables, including cultural values, moral imperatives, and institutional influences, which are increasingly pertinent to the European Green Deal and national sustainability strategies [8].

Notwithstanding its constraints, the Technology Acceptance Model (TAM) remains fundamental for understanding the adoption of new technologies by individuals and organisations. Its simplicity, predictive capability, and flexibility render it a significant model, particularly when combined with comprehensive frameworks that consider social, environmental, and policy aspects.

B. Theory of Planned Behavior (TPB)

The Theory of Planned Behaviour (TPB), formulated by Ajzen (1991), enhances the preceding Theory of Reasoned Action (TRA) by integrating the concept of Perceived Behavioural Control (PBC) [9]. The Theory of Planned Behaviour posits that three principal elements influence behavioural intentions: Attitude towards the behaviour, Subjective Norms, and Perceived Behavioural Control. Collectively, these structures elucidate the rationale behind people's formation of intentions to act and the subsequent translation of these intentions into real behaviour.

The Theory of Planned Behaviour (TPB) has been extensively utilised in psychology, marketing, environmental management, and sustainability research. Its efficacy resides in its ability to encompass both logical assessments and the impact of social norms and perceived control, rendering it particularly appropriate for

circumstances where cultural and institutional elements are significant [10]. For example, in the realm of sustainable consumption research, the Theory of Planned Behaviour (TPB) has been used to predict intentions to recycle, adopt renewable energy solutions, or purchase eco-friendly products [11].

Recent modifications of the Theory of Planned Behaviour underscore the significance of including moral identity, corporate culture, and environmental consciousness into the paradigm. Zhai (2025) introduced an Extended Theory of Planned Behaviour (ETPB) by integrating moral identity and corporate green culture, therefore enhancing the model's prediction capability for pro-environmental behaviour among megaproject contractors [12]. Rizaldy (2025) similarly combined the Theory of Planned Behaviour (TPB) with the Diffusion of Innovations (DOI), demonstrating that the features of innovation interact with social and control variables to elucidate the uptake of green technologies [13].

Furthermore, the Theory of Planned Behaviour (TPB) has demonstrated efficacy when integrated with the Technology Acceptance Model (TAM) in examining technology uptake within sustainability-oriented frameworks. Dong et al. (2022) utilised an integration of the Technology Acceptance Model (TAM) and the Theory of Planned Behaviour (TPB) to examine the adoption of agro-ecological technology by Chinese farmers, revealing that perceived utility (from TAM) and subjective norms (from TPB) collaboratively influence behavioural intentions [14].

Despite its extensive application, the Theory of Planned Behaviour (TPB) has faced criticism for its excessive dependence on intention as a mediator, inadequately resolving the disparity between intention and actual behaviour. This constraint is especially pertinent in sustainability, where individuals may have pro-environmental goals yet fail to act in accordance owing to structural or economic impediments. Bridging this gap necessitates augmenting the Theory of Planned Behaviour with models that include situational and institutional variables.

C. Diffusion of Innovations (DOI)

The Diffusion of Innovations hypothesis (DOI), proposed by Rogers (1962; 2003), is a seminal and very important paradigm for elucidating the temporal dissemination of innovations within a social system. The pace of adoption is influenced by five principal properties of innovation: Relative Advantage, Compatibility, Complexity, Trialability, and Observability, as per DOI. Furthermore, DOI classifies adopters into categories—innovators, early adopters, early majority, late majority, and laggards—according to their readiness to accept novel concepts [16].

The efficacy of DOI resides in its capacity to encompass both individual-level perceptions and system-level diffusion processes, rendering it a prevalent model in technology management, healthcare, and environmental research [17]. For example,

it has been utilised to examine the uptake of renewable energy, eco-innovations, and digital platforms for sustainability [18].

In recent years, experts have underscored the necessity to revise DOI by integrating behavioural realism and systemic viewpoints. Galster (2025) advocated incorporating behavioural realism into diffusion models, emphasising that cultural and policy contexts substantially affect adoption trajectories [19]. Takahashi (2024) re-examined innovation diffusion processes, demonstrating that digital ecosystems transform the way inventions achieve critical mass within society [20].

Karakaya and Sarkar (2014) examined the transmission of eco-innovation and identified obstacles like substantial initial costs, regulatory ambiguity, and consumer scepticism, which frequently impede the extensive use of sustainable technology [21]. Khan et al. (2022) have utilised DOI in healthcare to examine the uptake of green innovation in hospitals, highlighting the significance of organisational preparation and leadership support [22].

Although the DOI framework is fundamental, it has faced criticism for neglecting the significance of social impact, institutional issues, and psychological elements, which are more clearly considered in models like TPB or UTAUT. Nonetheless, DOI persists in offering significant insights into the dynamics of sustainability transitions, particularly when integrated with behavioural or acceptance models.

D. Unified Theory of Acceptance and Use of Technology (UTAUT)

The Unified Theory of Acceptance and Use of Technology (UTAUT), proposed by Venkatesh et al. (2003), serves as a comprehensive framework that integrates components from eight preceding theories, such as TAM, TPB, DOI, and the Innovation Diffusion Theory [23]. UTAUT delineates four primary factors of intention and usage: Performance Expectancy, Effort Expectancy, Social Influence, and Facilitating Conditions. The model also incorporates moderators such as gender, age, experience, and voluntary usage.

The UTAUT2 paradigm was subsequently expanded to include Hedonic Motivation, Price Value, and Habit, hence broadening its relevance to consumer scenarios outside organisational environments [24]. The growth of UTAUT has rendered it one of the most extensively utilised models in information systems and technology adoption research, especially concerning digital transformation and consumer-oriented technologies [25]. Recent studies have shown the effectiveness of UTAUT in the adoption of sustainability and green innovation. Selvi and Önem (2025) utilised UTAUT2 to examine the intention to adopt completely electric vehicles, demonstrating that performance expectancy and price value strongly impacted adoption choices [26]. Champahom et al. (2025) linked UTAUT2 with governmental policy aspects to analyse electric vehicle adoption across various vehicle types, affirming that conducive conditions and societal impact are essential

in mobility transitions [27]. Limpasirisuwan (2025) enhanced the model by including environmental awareness, hence augmenting its predictive capacity for battery electric vehicle (BEV) adoption [28].

Studies based on UTAUT in developing economies have highlighted the significance of institutional support and governmental incentives. Pratiwi (2024) integrated UTAUT2 with trust and policy satisfaction characteristics to elucidate EV uptake in Indonesia, emphasising the significance of contextual adaptability in sustainability-focused applications [29].

Despite its explanatory efficacy, UTAUT has faced criticism for its complexity and the necessity for significant contextual adaptation, which may restrict its parsimony in comparison to more straightforward models such as TAM. Its integrative character renders it especially effective for examining adoption in intricate situations where digital change, social impact, and sustainability objectives converge.

As shown in Table 1, each model offers unique explanatory variables that complement one another in sustainability-driven adoption studies.

Table 1. Comparative summary of adoption models

Model	Key Insights for Digital & Sustainable Innovation
TAM (Technology Acceptance Model)	Emphasizes perceived usefulness and ease of use. Strong predictors in digital contexts (e.g., fleet management systems, green IT), but limited in capturing social and normative drivers.
TPB (Theory of Planned Behavior)	Focuses on attitudes, subjective norms, and perceived behavioral control. Valuable for explaining sustainability behaviors (e.g., recycling, EV adoption), but faces the intention–behavior gap.
DOI (Diffusion of Innovations)	Explains diffusion dynamics via relative advantage, compatibility, complexity, trialability, and observability. Effective at the system-level (e.g., large-scale EV or eco-innovation adoption), less precise at individual level.
UTAUT / UTAUT2	Integrates technological, social, and contextual factors (e.g., performance expectancy, social influence, facilitating conditions). High explanatory power for EV adoption and green tech, though more complex to apply.

III. Comparative analysis and synthesis

The four examined adoption models—TAM, TPB, DOI, and UTAUT—offer complementary insights on innovation uptake. Each model has been verified across several domains; nevertheless, their explanatory efficacy differs based on the context and nature of the invention.

TAM provides a concise and highly predictive approach, focusing on judgements of utility and user-friendliness from a technology standpoint. This renders it especially appropriate for examining user interactions with digital platforms or onboard technology in electric vehicles, such as telematics, route optimisation systems, or fleet management software [30]. Nevertheless, the Technology Acceptance Model (TAM) alone fails to comprehensively account for the influence of regulatory incentives or organisational pressures that frequently dictate widespread adoption in freight mobility.

The Theory of Planned Behaviour enhances the analysis by incorporating social and normative aspects. Logistics operators in electric truck mobility frequently evaluate economic efficiency with reputational considerations and adherence to stakeholder expectations [31]. Subjective norms, such as client demand to decarbonise supply chains, and perceived behavioural control, including infrastructure availability and charging networks, directly influence adoption intentions. Nonetheless, the Theory of Planned Behaviour (TPB) encounters difficulties in bridging the intention–behavior gap, as individuals may articulate a readiness to adopt but ultimately refrain from action due to substantial investment costs or regulatory ambiguities.

DOI provides a system-level viewpoint, emphasising the attributes of innovation and classifications of adopters. In freight transportation, early adopters of electric vehicles are often major logistics companies or multinational corporations with environmental pledges, whereas smaller operators tend to be more cautious. The DOI elucidates how trialability and observability, shown by pilot projects demonstrating the efficacy of electric vehicles in urban distribution, may expedite broader dissemination. Nevertheless, DOI is less efficacious in forecasting individual decision-making within organisations, particularly where adoption necessitates intricate cost–benefit evaluations.

UTAUT and UTAUT2 amalgamate several constructs, rendering them exceptionally effective for elucidating adoption within intricate ecosystems such as urban freight electrification. Research indicates that performance expectancy (e.g., reduced long-term operating expenses), effort expectancy (e.g., seamless integration with digital fleet systems), and supportive conditions (e.g., governmental subsidies, charging infrastructure) are essential drivers [33]. Social influence significantly impacts firms as they strive to conform to competition and regulatory standards. Nonetheless, the model's complexity may pose difficulties for empirical validation

across various logistics marketplaces. Collectively, these frameworks indicate that no one model can comprehensively encapsulate the adoption processes of sustainability-driven breakthroughs like electric truck mobility. TAM is optimal for assessing technical usability, TPB emphasises behavioural and normative influences, DOI elucidates systemic dissemination, and UTAUT offers a comprehensive integration of technological, social, and environmental elements. An integrated approach that amalgamates various views provides the most thorough comprehension of the adoption of digital and sustainable technologies for both researchers and practitioners.

IV. Discussion: towards an integrated approach

The comparison research indicates that no singular adoption model adequately encompasses the intricacies of digital and sustainability-focused technologies. TAM elucidates technology perceptions, TPB highlights behavioural and normative implications, DOI addresses systemic spread, and UTAUT synthesises several determinants. Collectively, these viewpoints emphasise the necessity for a cohesive strategy in the adoption of innovation.

In the realm of sustainability transitions, especially concerning transportation and logistics, such integration is essential. The adoption of electric trucks for urban freight transport cannot be entirely attributed to perceived utility, as suggested by the Technology Acceptance Model, or to innovative features, as emphasised by the Diffusion of Innovations theory. Adoption is contingent upon a confluence of technological perceptions (e.g., cost efficiency, user-friendliness), behavioural factors (e.g., attitudes towards sustainability, normative pressures from clients and regulators), systemic characteristics (e.g., infrastructure preparedness, visibility of successful pilot initiatives), and contextual facilitators (e.g., policy incentives, conducive conditions).

This indicates that hybrid models—like TAM-TPB or UTAUT extensions incorporating sustainability constructs—provide enhanced explanatory capacity for both research and practice [34]. Recent research on the proliferation of electric vehicles and renewable energy has demonstrated that including environmental considerations, policy understanding, and organisational preparedness into adoption frameworks is successful [35].

From a management perspective, this comprehensive viewpoint allows decision-makers to formulate adoption strategies that extend beyond technology design and usability. Logistics firms contemplating the deployment of electric trucks must assess fleet management efficiency, regulatory compliance, market reputation, and long-term sustainability objectives. Governments and policymakers may utilise this by customising subsidies, infrastructure investments, and communication initiatives to target both rational and normative factors influencing adoption. The

integration of TAM, TPB, DOI, and UTAUT facilitates a multi-tiered research program.

- Micro-level: comprehending the individual decision-making processes of managers and drivers.
- Meso-level: examining organisational strategy and supply chain dynamics.
- Macro-level: examining diffusion trajectories influenced by legislation, incentives, and cultural values.

An integrated model for innovation uptake in sustainable transportation and digital transformation must extend beyond conventional predictors to include behavioural realism, institutional forces, and sustainability imperatives.

V. Conclusions

This research presents a comparative literature-based analysis of four predominant innovation adoption models—TAM, TPB, DOI, and UTAUT—within the framework of digital transformation and sustainability. The research indicated that although each model offers useful insights, none alone can adequately elucidate adoption processes in intricate fields such as electric transportation, green logistics, or renewable energy technology.

The Technology Acceptance Model (TAM) is crucial for understanding technology-specific perceptions of utility and user-friendliness, while the Theory of Planned Behaviour (TPB) addresses social and normative influences that are vital for sustainable transitions. DOI highlights diffusion dynamics and adopter classifications at the systemic level, whereas UTAUT amalgamates several variables into a comprehensive explanatory framework, particularly relevant for consumer and organisational settings.

The synthesis indicates that integrative approaches—merging technological, behavioural, systemic, and contextual perspectives—hold the most promise for enhancing both theory and practice. The use of electric trucks in urban freight transportation necessitates user acceptance of digital fleet technologies, normative alignment, infrastructural preparedness, and conducive policy frameworks.

This study underscores the need to enhance existing models by including characteristics associated with environmental concern, institutional trust, and sustainability imperatives. From a management standpoint, it emphasises the necessity of formulating adoption strategies that concurrently tackle technology usability, social legitimacy, and systemic feasibility.

Ultimately, enhancing the future of digital and sustainable innovation management requires transcending fragmented theoretical perspectives in favour of comprehensive frameworks that integrate innovation adoption with overarching social and environmental objectives. The article advances this objective by

providing a systematic comparative synthesis and delineating avenues for integrated adoption research.

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EFFICIENCY ENABLES INCLUSION: THE CRITICAL PATH METHOD APPLIED IN A CIRCULAR SOCIAL ENTERPRISE

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Abstract

This article analyzes the application of the Critical Path Method in a work integration social enterprise operating within the circular economy. Using the case of OilRight, a Romanian social business valorizing used cooking oil, the article examines how CPM-based resource mapping and reallocation improved production efficiency and reduced labor costs, while simultaneously enhancing team cohesion and employee satisfaction. The findings demonstrate that operational planning tools can stabilize inclusive circular business models, supporting both economic viability and social impact at the micro-production level.

Keywords

Circular economy; work integration social enterprise; critical path method; production planning; impact; Romania; used cooking oil; disability.

I. Introduction and literature review

The circular economy is no longer treated simply as a set of “green practices”, but as a strategic framework that seeks to change the relationship between resources, production and consumption. At the European Union level, the New Circular Economy Action Plan has shifted the focus to interventions across the entire product life cycle [1].

In parallel, recent reports show a clear tension between ambition and reality: global circularity does not automatically increase with the popularity of the concept. The Circularity Gap Report 2024 notes that the share of secondary materials

consumed by the global economy has decreased, suggesting that systemic progress is fragile and dependent on concrete economic and operational mechanisms [2]. In the same vein, the World Bank argues that decoupling economic growth from material consumption is possible, but requires coherent policies (fair prices, information, investments) and, at the micro level, real implementation capabilities in organizations and communities [3].

The specialized literature increasingly converges towards the idea that the circular economy is materialized, in practice, through circular business models. These are not limited to recycling, but include strategies such as life extension, reuse, repair, remanufacturing and material recovery – that is, redesigning the value stream, not just its end [4]. The extensive review by Geissdoerfer et al. shows two useful things for the article: (1) circular models are real levers for implementation, but (2) there are still conceptual ambiguities and the risk that “circular” will remain a label if not supported by processes, indicators and stable relationships with partners [4]. In addition, research is starting to be more direct about “side effects” such as rebound effects: situations where a circular solution, although locally efficient, can stimulate total consumption or shift the impact elsewhere. A review dedicated to rebound in circular models shows that these effects exist, are context-dependent and can be reduced only if the model is also thought of as sufficiency (not just efficiency), with realistic mitigation mechanisms and evaluations [15]. Basically, the message is that the circular economy is not judged only by what it reuses, but also by how it is organized and what behaviors it generates.

Another strong wave in the literature in recent years concerns the social dimension: the quality of work, inclusion, equity and distribution of benefits. Padilla-Rivera and colleagues show, in a systematic review, that although interest in the social component is growing, the measurement of social impact in the circular economy is still fragmented and inconsistent [5].

In practice, social enterprises are seen as accelerators of circularity, precisely because they can combine activities to close material loops (collection, sorting, reconditioning, upcycling) with goals of inclusion and community development. The Inclusive Loops report describes the typical roles through which social enterprises contribute to circularity and insists on the barriers to scaling: resource stability, infrastructure, financing, as well as the operational delivery capacity (timelines, quality, costs) [6].

This concern also appears in the very recent academic literature through the concept of social circular hubs, described as structures that connect administration, knowledge institutions, the private sector and civil society to accelerate circular solutions and make them more accessible to different groups [7]. In addition, an applied study on Work Integration Social Enterprises in the circular economy warns that job creation and social impact cannot be assumed, especially in specialized markets: organizations need realistic economic models, operational capabilities and

ecosystems that support the transition [8]. A useful piece here is the report on “inclusive circularity”, which directly discusses the link between circularity and decent jobs, emphasizing the need for a circular transition that is also socially just (skills, working conditions, complementary policies) [9].

Used cooking oil is increasingly treated as a circular resource, but the literature shows that its valorization critically depends on properties, collection and storage. A 2024 review highlights that degradation and contamination directly affect quality and subsequent uses; thus, collection and storage are already part of the technological process, not just logistics [10].

In parallel, research on collection infrastructure shows that system performance depends on point location, accessibility, costs, and compliance, especially when the main source is dispersed (households, multiple points) and volumes are small and variable [11].

The critical path method remains relevant for processes with interdependent activities precisely because it forces the explicitation of sequences, durations and dependencies. In micro-production, the critical path method has an advantage: it transforms a typical flow into a verifiable route, where you can see where delays propagate and which activities determine the final deadline. However, recent research highlights uncertainty: real-time varies due to human factors, interruptions, and a lack of materials. Hazır and Ulusoy show that the literature has often modeled the uncertainty of durations, but has treated less other sources (resources, external disturbances, supply), although in practice these can be decisive [12].

In this context, approaches such as the critical path method are proposed as ways to realistically treat estimated durations, especially in environments where there are no long data series or where activities are sensitive to variability [13]. Along the same lines, Critical Chain Project Management becomes relevant when the main constraint is the shared resource (people/equipment) and when multitasking consumes capacity without being visible in the plan. A recent systematic review on Critical Chain Project Management synthesizes applications and trends (including integrations with lean approaches and digital tools) and emphasizes the role of buffers as a protection mechanism in conditions of variability [14]. For a local circular model, this literature supports a pragmatic idea: if the input is variable, production planning must be all the more disciplined, otherwise bottlenecks and losses appear (waiting times, lack of material or capacity, overstock) [15].

Taken together, these directions tell a coherent story: the circular economy needs business models and infrastructure, the social dimension requires decent jobs and community benefits, and waste oil as a secondary resource brings real potential, but also variability (quality, collection, flow). What is less often seen in the state-of-the-art literature is the explicit link between these paradigms and concrete operational tools applied in micro-production units that work with recovered input and also

pursue social objectives. A study that deals with the critical path between jobs, together with the logic of variability and the management of constraints, can fill this gap with an applied contribution: it shows how to stabilize a circular model with social impact at the execution level (times, dependencies, bottlenecks, deadlines) and how to avoid the situation where the mission is strong, but the operational remains fragile.

II. OilRight – a local work integration circular economy social enterprise

A. Legal and operational framework

The social economy, as defined in European and Romanian policy frameworks, represents a distinct way of organizing economic activities: one in which the prevalence of social purpose over profit maximization is organizationally embedded. Unlike traditional CSR-oriented businesses, social economy enterprises integrate social (and/or environmental) objectives directly into ownership, governance, and profit distribution mechanisms.

In Romania, Law no. 219/2015 provides a clear legal structure for social enterprises, emphasizing priority to social objectives, democratic governance, limited profit distribution, and asset lock provisions. These criteria move social impact from intention to legal obligation.

OilRight, created in 2020, is explicitly incorporated as a work integration social enterprise, as the constitutive act embeds social economy principles at multiple levels:

- Declared social purpose: social inclusion of vulnerable groups, environmental protection, and sustainability education;
- Profit reinvestment: minimum 90% of profit allocated to social objectives and statutory reserves;
- Wage equity: maximum 1:8 salary ratio;
- Democratic control: equal voting rights per share, transparent decision-making;
- Asset lock: transfer of remaining assets upon liquidation to other social enterprises.

Moreover, the composition of the founding team reflects the commitments to inclusion and the vision for long term partnerships, values-based growth and impact. The five co-founders (one majority, owning 52%, the other four - 12% each), with diverse backgrounds (including one person with intellectual disability, from an ethnic minority) and strong connections with each other decided to create a social business that would have to comply with two main criteria: create jobs for persons with disabilities and contribute in a positive way to the environment.

B. Business model and operationalization

OilRight operates on a circular economy model centered on used cooking oil (UCO), a highly polluting household and hotels, restaurants, and cafés/catering (HoReCa) waste.

Improper disposal of UCO, in general via household sinks or sewage systems, represents a disproportionate environmental burden. UCO contributes to:

- Severe water pollution due to oxygen reduction
- Clogging and corrosion of sewage infrastructure
- Increased energy demand and chemical use in wastewater treatment plants.

It is widely accepted in environmental engineering that 1 liter of improperly disposed UCO can contaminate up to 1,000,000 liters of freshwater [16]. OilRight's model follows a simple logic:

- Collection of UCO from households and HoReCa partners;
- Transformation, based on the circular economy principles, into raw material for biodiesel and upcycled products;
- Reinvestment of revenues into employment, education, development and awareness activities and financial donations to a charity supporting community living for adults with disabilities;
- Education aimed at behavioral change leading to increased UCO collection volumes and a more inclusive mindset.

OilRight provides a combination of services and products that build on one another for sustained social, environmental, and economic impact. The services are centered around education, as a driver to challenge the two core problems identified by the founding team, prior to the launch of the business:

- Information and awareness deficit
 - Most individuals were unaware of the environmental harm caused by improper UCO disposal (sewage blockages, water contamination, increased water treatment costs for local water management companies).
 - UCO was not perceived as a distinct waste category demanding special handling.
- Lack of accessible UCO collection options
 - Even when individuals were aware of the problem, they lacked practical, at-hand solutions.
 - Absence of nearby collection points discouraged consistent behavior change.

As a result, OilRight systematically invested in education and infrastructure, treating them as complementary components of a single mechanism, core to its business model. The services provided are:

- i. Household activation: information campaigns and direct engagement to transform households into active waste collectors;

- ii. Educational workshops for children: hands-on learning about waste, circularity and responsibility;
- iii. Corporate workshops: ESG-oriented sessions combining awareness, team-building and practical sustainability actions.



Fig. 1. Information

Fig. 2. Educational and corporate workshops campaign

OilRight developed three product lines for the UCO, based on circular economy principles. Each has its own production flow:

- i. Raw material for biodiesel: sold to specialized processors, contributing to renewable energy chains;
- ii. Eco candles: produced from recycled cooking oil, marketed as low-impact alternatives to paraffin candles;
- iii. DIY candle kits: combining product sales with environmental education.



Fig.3. Products: UCO for biodiesel, ecological candle, DIY kit

In the coming section, the article will assess in detail the first two products, using the critical path method, in order to understand the flow of activities for each, their interdependencies, and make practical suggestions on how to properly allocate the limited organizational resources. The social enterprises employs persons with intellectual, psychosocial and visual disabilities, a team that, despite various challenges, has the ability to synchronize itself in complex situations, even when the flows of activities are not always clear and structures. The paper helps the operational team to make the overall production flow more efficient. For this goal, the authors identified the activities, configured the network of operations and adjusted it in order to ensure optimal resources allocation.

III. Methodology

Methodologically, this article extends the application domain of CPM to micro-production systems with high variability and social objectives, an area rarely addressed in project management research. In practice, the results suggest that even small circular social enterprises can benefit from classical operations management tools, provided they are adapted to human diversity and resource constraints. The methodological framework used for this article follows three logical steps:

A. Conceptualization

OilRight operates an integrated waste valorization model targeting UCO, combining two complementary product lanes:

- 1) Authorized UCO collection and aggregation, supplying secondary raw materials for biodiesel production and ecological candle manufacturing.
- 2) A Do-It-Yourself (DIY) home upcycling kit, enabling decentralized, household-level transformation of UCO into a new product, eliminating the collection efforts and preventing pollution at source.

This dual system allows OilRight to have an impact at multiple points of the UCO lifecycle, addressing both systemic waste management failures and behavioral drivers of pollution.

The article focuses on the first lane and assesses the two resulting products. The first, generating UCO for biodiesel production means, for OilRight, transferring the UCO from individual household or restaurants recipients into Intermediate Bulk Containers (IBCs), in order to consolidate distributed small volumes into logistics-efficient units. The next steps are to store it in designated facilities, manage the waste generated by household recipients, and sell the UCO to biodiesel producers. All these, in a documented way, are compliant with national and European traceability. The later product, the ecological candle, results after upcycling, based on quality assessments, a portion of the collected UCO. The UCO is mixed with a certified non-toxic wax. The candle is designed and produced in accordance with green chemistry principles, prioritizing renewable and waste-based raw materials, reducing toxicity during combustion, lower embodied energy relative to paraffin candles and fragrances avoiding essential oils whose production is associated with high land use, pesticide application, and energy-intensive transport.

The two products share the upstream supply chain, as follows:

- UCO pick-up from households (small volumes, high frequency) and HoReCa (large volumes, lower frequency);
- Transportation to OilRight's premises;
- Physical reception and storage;

- Documentation and reception registers (per point of origin);
- UCO assessment: separation into UCO for biodiesel and UCO for candles.

From this activity onwards, the UCO follows two distinct flow chains. The UCO for biodiesel is transferred into large barrels, stored, and then sold, while the waste generated by this activity is properly managed.

The ecological candles production implies: centrifugal filtration (removal of solids, other residues, water and salts), heating, formulating and mixing with the wax (dosing wax powder, as per the recipe and the fragrance required by the clients, mixing at a controlled temperature), jars preparation (which include jar cleaning / inspection and jar labeling with the type of cent to be poured), pouring (manual activity, with level control), wick positioning, cooling time, taking away the wick holder and trimming the wick, cleaning and quality control, placing the cork lids, labelling (with the same scent as the jars) and stamping the date of the production on the boxes), boxing the candles, shelves storing and sales.

The list of activities is presented in Table 1, providing information on the duration of each activity, its predecessors and the needed resources, as required by the critical path method. Based on this information, the production flows will be modeled, in order to improve the management of this project, considering its interdependent activities and the limited resources the company has (four operators, three of them with disabilities, only one working full time).

Table 1. List of activities

Activities		Used cooing oil (UCO) for biodiesel (BD)				Eco candles (EC)		
ID	Task name	Duration (hr)	New hr	Predecessors	Operators	Duration (hr)	Predecessors	Operators
A	UCO pick-up from households and restaurants	2	1	-	O1, O2, O3, O4	2	-	O1, O2, O3, O4
B	Transportation	0.5		A	O1	0.5	A	O1
C	Physical reception	0.4	0.16	B	O2	0.4	B	O2
D	Documentation	0.16		C	O1	0.16	C	O1
E	UCO assessment	0.35	0.33	D	O2	0.35	D	O2
F	UCO for BD in big barrels	0.5		E	O1, O2			
G	UCO for EC in big barrels					0.2	E	O3, O4
H	Small barrels / waste recipients management	0.5		E	O1	0.5	E	O1
I	Storage UCO for BD	0.5	0.33	F	O2, O4			
J	Sales UCO for BD	0.5		I	O1, O4			
K	Centrifugal filtration					1	G	O1, O2
L	Heating					0.5	K	O2
M	Formulation&mixing with wax					1.5	L	O2
N	Jars preparation					1.25	-	O3
O	Pouring					1.67	M, N	O2
P	Wick positionning					0.5	O	O3
Q	Cooling time					1	P	idle time
R	Taking away the wick holder and trimming the wick					0.5	Q	O3
S	Cleaning and quality control					0.83	R	O4
T	Placing cork lid					0.5	S	O2
U	Labelling and stamping the date of the production on the boxes					2.5	-	O4
V	Boxing					0.16	T, U	O2
X	Shelves storing					0.16	V	O3, O4
Y	Sales of EC					0.16	X	O1

B. Configuration

Using the critical path method, the authors configured the logical network for the main production flows, using the precedence relationships between the different activities. Based on this network, the planning and resource allocation can be improved.

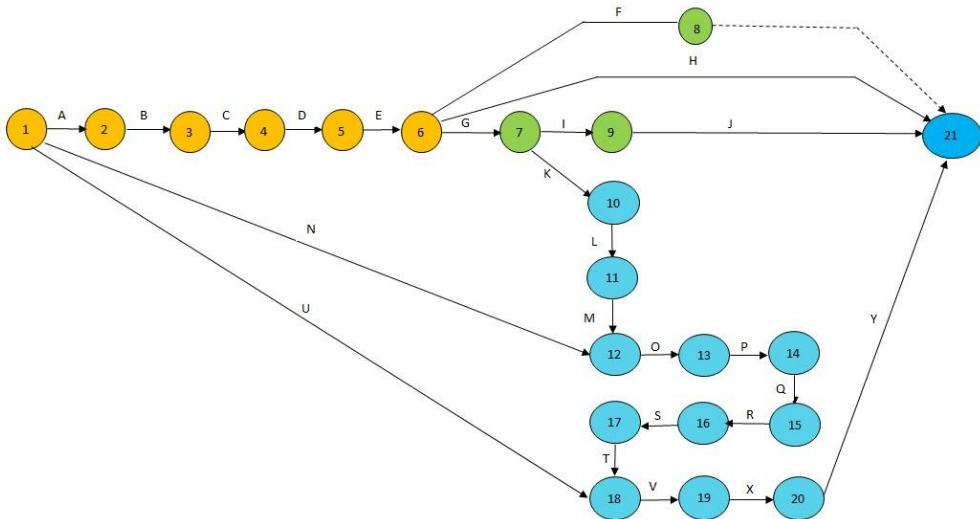


Fig. 4. Biodiesel and candles production network

As a next step, the authors evaluated, in detail, the allocation of two out of the four operators: O2, a full-time employee with psycho-social disabilities, and O3, working part time, employee with visual disabilities. Based on the initial input data from the entrepreneur, the workload per operator is the following:

	O2	9.08 hrs	Work	8.42h	0.67h
	A - UCO pick-up from households and restaurants	2 hrs	Work	2h	
	C - Physical reception	0.4 hrs	Work	0.4h	
	E - UCO assessment	0.35 hrs	Work	0.35h	
	F - UCO for BD in big barrels	0.5 hrs	Work	0.5h	
	I - Storage UCO for BD	0.5 hrs	Work	0.5h	
	K - Centrifugal filtration UCO for EC	1 hr	Work	1h	
	L - Heating	0.5 hrs	Work	0.5h	
	M - Formulation and mixing with wax	1.5 hrs	Work	1.5h	
	O - Puring	1.67 hrs	Work	1.67h	
	T - Placing cork lid	0.5 hrs	Work		0.5h
	V - Boxing	0.17 hrs	Work		0.17h

Fig. 5. Initial workload for operator 2

	O3	4.53 hrs	Work	4.45h	0.08h
	A - UCO pick-up from households and restaurants	2 hrs	Work	2h	
	G - UCO for EC in big barrels	0.2 hrs	Work	0.2h	
	N - Jars preparation	1.25 hrs	Work	1.25h	
	P - Wick positionning	0.5 hrs	Work	0.5h	
	R - Taking away the wick holder and trimming the wick	0.5 hrs	Work	0.5h	
	X - Shelves storing	0.08 hrs	Work		0.08h

Fig. 6. Initial workload for operator 3

C. Resource planning: adaptation strategies

Once the overload per operator was understood (O2 and O3 are overloaded with tasks, considering the available working time), the authors identified ways to adjust the human resources involvement per activity, in order to increase efficiency, while considering the challenges specific to each member of the team and the limited number of available staff. This led to an adjustment in the time estimate for completing both production flows, as shown in the figures below.

▲ O2	6 hrs		Work	5.33h	0.67h
A - UCO pick-up j	1 hr		Work	1h	
C - Physical recept	0.17 hrs		Work	0.17h	
E - UCO assessm	0.33 hrs		Work	0.33h	
F - UCO for BD in	0.5 hrs		Work	0.5h	
I - Storage UCO j	0.33 hrs		Work	0.33h	
K - Centrifugal fil	0.83 hrs		Work	0.83h	
L - Heating	0.17 hrs		Work	0.17h	
M - Formulation	0.33 hrs		Work	0.33h	
O - Puring	1.67 hrs		Work	1.67h	
T - Placing cork li	0.5 hrs		Work		0.5h
V - Boxing	0.17 hrs		Work		0.17h

Fig. 7. Suggested workload for operator 2

▲ O3	2.67 hrs		Work	2.58h	0.08h
A - UCO pick-up j	0.5 hrs		Work	0.5h	
G - UCO for EC in	0.17 hrs		Work	0.17h	
N - Jars preparat	1.25 hrs		Work	1.25h	
P - Wick position	0.25 hrs		Work	0.25h	
R - Taking away	0.42 hrs		Work	0.42h	
X - Shelves storin	0.08 hrs		Work		0.08h

Fig. 8. Suggested workload for operator 3

The activities whose duration was impacted by the proposed resource allocation are marked in red in the following table, leading to time savings for O2 (3.08 hours) and O3 (1.86 hours).

Table 2. List of activities: new times

Activities		Used cooking oil (UCO) for biodiesel (BD)				Eco candles (EC)			
ID	Task name	Duration (hr)	New (hr)	Predecessors	Operators	Duration (hr)	New (hr)	Predecessors	Operators
A	UCO pick-up from households and restaurants	2	1	-	O1, O2, O3, O4	2	0.5	-	O1, O2, O3, O4
B	Transportation	0.5		A	O1	0.5		A	O1
C	Physical reception	0.4	0.16	B	O2	0.4		B	O2
D	Documentation	0.16		C	O1	0.16		C	O1
E	UCO assessment	0.35	0.33	D	O2	0.35		D	O2
F	UCO for BD in big barrels	0.5		E	O1, O2				
G	UCO for EC in big barrels					0.2	0.16	E	O3, O4
H	Small barrels / waste recipients management	0.5		E	O1	0.5		E	O1
I	Storage UCO for BD	0.5	0.33	F	O2, O4				
J	Sales UCO for BD	0.5		I	O1, O4				
K	Centrifugal filtration					1	0.83	G	O1, O2
L	Heating					0.5	0.16	K	O2
M	Formulation&mixing with wax					1.5	0.33	L	O2
N	Jars preparation					1.25		-	O3
O	Pouring					1.67		M, N	O2
P	Wick positioning					0.5	0.25	O	O3
Q	Cooling time					1		P	idle time
R	Taking away the wick holder and trimming the wick					0.5	0.41	Q	O3
S	Cleaning and quality control					0.83		R	O4
T	Placing cork lid					0.5		S	O2
U	Labelling and stamping the date of the production on the boxes					2.5		-	O4
V	Boxing					0.16		T, U	O2
X	Shelves storing					0.16		V	O3, O4
Y	Sales of EC					0.16		X	O1

The application of the critical path method to OilRight's dual production flow (UCO for biodiesel and ecological candles) generated measurable operational, economic, and social improvements. Beyond planning clarity, CPM functioned as an organizational learning tool, transforming implicit knowledge into explicit coordination rules.

The reallocation of activities between operators O2 and O3 resulted in a net time saving of 4.94 hours per production cycle (3.08 hours for O2 and 1.86 hours for O3). These savings were achieved without task elimination, but through parallelization of non-dependent activities, relocation of tasks better aligned with operators' cognitive and sensory capabilities and reduction of idle and waiting times. At the

system level, the critical path duration for candle production was reduced by approximately 11–15% (depending on batch size), while the biodiesel preparation flow experienced a stabilization of lead time. This stabilization is particularly relevant in a context of variable input quality and volumes, as it happens in practice.

Labor productivity increased as effective working time replaced coordination losses. Following CPM-based reallocation, the productivity increased by an estimated 12–18% for candle production. The same workforce can now process either a higher volume of UCO within the same timeline, or the same volume with lower cognitive and physical pressure. Capacity utilization improved mainly for operator O3, whose tasks were restructured to minimize unnecessary context switching and focus to a wide range of subtasks.

From a microeconomic perspective, the time savings mean reduced unit labor costs, improving the contribution to the overall profit margin of the ecological candles, which have higher value-added but are also more labour-intensive than UCO sales as raw material for biodiesel. OilRight can expect an 8–12% reduction in unit labor cost for candles and improved cash flow predictability due to shorter and more reliable production cycles. These effects improve the economic viability of this social enterprise model, where profit reinvestment and wage equity limit traditional cost-cutting strategies.

Improved productivity and lower unit costs increase operating surplus, even if prices remain the same. This financial surplus is critical for OilRight, because at least 90% of profits are reinvested into social objectives. CPM therefore indirectly increases funds available for job creation and skill development, for reinvestments or donations to the disability cause, or resilience against product demand fluctuations, without operational stress.

Beyond quantitative indicators, CPM had qualitative organizational effects. Clear task sequences and evident dependencies reduced uncertainty and anxiety among operators (especially relevant for those with psycho-social disabilities), reinforced mutual trust and coordination, increased perceived fairness in workload distribution. For employees with disabilities, predictability and role clarity (one of them has an autistic spectrum disorder) are decisive factors for job satisfaction and long-term retention. The reduction of overload on O2 and O3 translated into higher engagement and fewer fatigue or anxiety-related pauses. Team cohesion improved as the production flow became a shared reference rather than an implicit expectation, always relying on someone else. In this sense, CPM acted as a tool improving efficiency while reinforcing dignity at work.

IV. Conclusion and further research

The findings of this article directly respond to current debates in circular economy and social enterprise research regarding the implementation gap between strategic

intent and operational execution. While literature mainly emphasizes business models, governance, and ecosystem conditions, this case demonstrates that operational planning tools are a critical but underexplored enabler of circular and inclusive value creation.

This article demonstrates that classical project management tools, such as the Critical Path Method, remain relevant when applied in non-traditional contexts such as circular economy social enterprises. At OilRight, CPM enabled the stabilization of a micro-production system characterized by variable inputs, limited resources, and strong social objectives.

The results show that time savings at the operator level can generate significant benefits at system level: increased productivity, lower unit costs, improved profitability, and increased reinvestment capacity. Beyond economic performance, CPM contributed to higher team cohesion, reduced stress, and improved job satisfaction, particularly for employees with disabilities. These outcomes underline that operational rigor and social inclusion are mutually reinforcing when processes are designed with human constraints in mind. The application of the Critical Path Method at OilRight shows that circularity is not only a matter of closing material loops, but also of clarifying time, workload, and decision-making structures. By making dependencies explicit and reducing hidden bottlenecks, CPM explains circular principles into workable practices.

From a social economy perspective, the article illustrates how productivity improvements and inclusion are not opposing goals. On the contrary, the rebalancing of workloads and clarification of the order of tasks increased both operational performance and employee well-being. This confirms that decent work in the inclusive circular economy depends on predictability, role clarity, and cognitive accessibility of work processes.

The use of CPM avoided the common risk identified on work integration social enterprises, that social missions mainly rely on informal coordination and individual goodwill. Instead, OilRight's experience shows how formal planning tools can protect vulnerable workers from overload and uncertainty, reinforcing dignity and long-term employability. The 2022 European Union's transition pathway on proximity and social economy, with its key action areas, confirms that models like OilRight can contribute to local development, in sustainable, inclusive and local community-relevant ways [17].

To conclude, the article proves that inclusive circular models require not only innovative business ideas, but also a well-organized process design capable of transforming inconsistency into practicable routines. However, the limited scope of this article opens opportunities for future research:

- Scaling effects: further research could analyze how CPM-based optimization performs when scaling volumes, partners, or product lines in inclusive circular models.

- Comparative methods: a comparison between CPM and lean approaches could expose complementarities or trade-offs in social enterprise situations.
- Social performance metrics: longitudinal studies could quantitatively link operational stability with indicators such as employee retention, absenteeism, and well-being.
- Digital integration: exploring digital planning tools adapted for inclusive workplaces could further develop coordination without increasing cognitive load.

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INDUSTRIAL SYMBIOSIS IN THE PULP AND PAPER INDUSTRY: CASE STUDIES AND TRENDS

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Abstract

Industrial Symbiosis (IS) has become a cornerstone of circular economy strategies, particularly in resource- and energy-intensive industries such as pulp and paper. This paper explores how IS contributes to sustainability transitions by analysing European flagship examples and Slovenian case studies. The analysis demonstrates that symbiotic exchanges in the sector are dominated by energy recovery, by-product valorisation, and increasingly, water reuse. Large-scale ecosystems such as Metsä Group's Äänekoski bioproduct mill, which produces 1.3 million tonnes of pulp annually and generates about 240% of its own energy needs, showcase the systemic integration of side streams into bio-industrial hubs. In contrast, smaller-scale Slovenian initiatives highlight innovative municipal-industrial linkages, such as district heating in Sladki Vrh or wastewater reuse in Ljubljana. The study finds that geographic proximity, shared infrastructure, and supportive EU policy frameworks are consistent enablers, while regulatory hurdles and market volatility remain key barriers. Taken together, the cases confirm that pulp and paper mills can act as central anchors in regional symbiosis networks, positioning the sector as a driver of Europe's green transition.

Keywords

Industrial Symbiosis, Circular Economy, Pulp and Paper Industry, By-product Valorisation, Wastewater Reuse, EU Green Deal

I. Introduction

A. Introduction to Industrial Symbiosis

Industrial Symbiosis is a key practice within industrial ecology that seeks to emulate the closed-loop efficiency of natural ecosystems in industrial systems. In essence, IS

involves the synergistic exchange of resources – such as waste materials, by-products, energy, and water - between different companies, so that the "waste" from one becomes a resource for another. [1, 2] This collaborative approach shifts industries away from the traditional linear "take-make-dispose" model toward a circular model where the outputs of one process serve as inputs for others. According to Chertow [3, 4], IS engages traditionally separate industries in a collective strategy for competitive advantage by physically exchanging materials, energy, water and/or by-products.

The purpose of this article is to build on that conceptual foundation and explore how IS can be applied in the pulp and paper industry. The article first introduces IS and its conceptual background, then considers how IS can be implemented, reviews case studies, and reflects on both the enabling conditions and barriers that shape these practices. It concludes with lessons for industry, policymakers, and the broader community. In terms of the research question, this article focuses on how pulp and paper mills can act as anchor points of industrial symbiosis, what enabling conditions and barriers shape these practices, and how lessons from flagship international cases can inform smaller-scale national contexts such as Slovenia.

B. Aspects of IS Implementation

For industrial symbiosis to be effective in practice, cooperation and proximity often play a crucial role. When companies operate in the same area, it becomes much easier to exchange resources and set up practical synergies. The role of IS in sustainable industrial ecosystems is, therefore, to close material loops, reduce the use of virgin resources and waste generation, and create an integrated industrial network that enhances both environmental and economic performance. In practice, IS can occur in various configurations – among co-located firms in an eco-industrial park, among companies in a region, or even virtually across wider distances via facilitated exchanges. By turning one firm's waste into another's input, industrial symbiosis helps to transform waste into valuable commodities, contributing directly to a more circular and sustainable economy. [2] This collaborative approach fosters innovation and resource efficiency and strengthens community ties. Local businesses work together to optimise their operations and share the benefits of reduced costs and environmental impact. [2, 5–7]

At its core, industrial symbiosis operates on the principle that "everything has its use", meaning one entity's residual outputs are another's raw materials. Several fundamental principles guide the implementation of IS: resource synergy, mutual benefit, and collaboration. [8] Participating firms identify opportunities where the waste or by-product of one process (such as excess heat, steam, sludge, or chemical by-products) can replace a resource in another process. Establishing these synergies often requires building trust and information-sharing among companies, sometimes

facilitated by a third-party broker or through formal networks. Key aspects of implementing IS include mapping resource flows, negotiating exchange agreements, and often making technical or logistical adjustments to enable the reuse of materials or energy streams. [1, 2]

Effective IS can emerge through both self-organised processes and deliberate facilitation. A famous example of a spontaneously developed symbiosis is the Kalundborg Symbiosis in Denmark [9, 10], which is widely regarded as the first full realisation of IS. Beginning in the 1960s and 1970s, through informal conversations among local managers, the Kalundborg network evolved to link an oil refinery, a power plant, a gypsum board facility, a pharmaceutical plant, and the city municipality in a web of exchanges. By the 1980s, these partners were regularly trading by-products and sharing utilities: for instance, the power plant's surplus steam is piped to the pharmaceutical and refinery operations, sludge from a biotech facility is used as fertiliser by nearby farms, fly ash from the power station is used in cement production, and residual yeast from insulin production becomes pig feed. This synergy evolved over decades based on economic logic and trust, without the need for top-down planning, and it was only later, in 1989, that the term "industrial symbiosis" was applied to describe it [11].

Industrial Symbiosis is a key enabler of the European Green Deal's goal of achieving climate neutrality by 2050 through a circular economy, where growth is decoupled from resource use and environmental harm (European Commission, 2021a; Haines & Scheelbeek, 2020). By reusing materials, energy, and by-products across industries, IS contributes directly to waste reduction, resource efficiency, materials security, greenhouse gas reduction, green growth, and innovation (Ashton, Chertow, & Althaf, 2022; Rungruang et al., 2023). The EU actively supports IS through its Circular Economy Action Plan and New Industrial Strategy (European Commission, 2020, 2021b), as well as funding programs such as Horizon 2020 and Horizon Europe, which foster digital platforms, cross-sectoral collaboration, and eco-innovation (Posselt, Haugk, & Bourayou, 2020). Policy measures, including clarifications in waste legislation, aim to facilitate symbiotic exchanges, while stricter landfill bans and rising waste costs are expected further to incentivise adoption (European Commission, 2015). Looking ahead, IS is set to play a central role in industrial decarbonisation, boosting Europe's competitiveness, creating new business opportunities and jobs, and building resilient, sustainable industrial ecosystems aligned with the EU's green and innovation-driven future (Domenech et al., 2019; Baldassarre et al., 2019; de Selliers & Spataru, 2019).

C. Positive and Negative Aspects of Industrial Symbiosis

The positive impacts of industrial symbiosis are significant for the environment, economy, and innovation. By treating waste as a resource, IS significantly reduces

the amount of waste sent to landfills and overall pollution. [12, 13] Materials and energy that would otherwise be discarded are continually recycled, thereby lowering the environmental footprint of industrial activities. For example, exchanges of excess energy or materials directly lead to waste diversion and less extraction of virgin resources, contributing to pollution prevention and resource conservation. IS also significantly improves resource efficiency, meaning industries can produce the same output with fewer inputs by harnessing each other's by-products. This increased resource productivity effectively decouples economic growth from resource consumption, a core goal of sustainability. One EU analysis estimated that scaling up industrial symbiosis could save €1.4 billion per year across the EU in raw material and waste management costs and generate an additional €1.6 billion in sales of new products and services. [14] Such economic gains result from reduced disposal costs, savings on raw materials, and sometimes the emergence of new revenue streams (by selling what was once considered waste). Indeed, industrial symbiosis is often touted as a "win-win" strategy that yields both cost savings and environmental benefits for participating firms.

Companies in symbiotic networks can realise direct financial benefits (e.g. cheaper feedstocks, avoided waste fees) while also cutting emissions and energy use by sharing resources. Moreover, the collaborative process of IS can spur innovation: firms must develop creative technical and logistical solutions to utilise unconventional inputs, which can lead to new technologies or products. As firms collaborate (even with competitors), the "coopetition" dynamic can drive them to innovate and improve their processes. [15] IS networks thus often become hotbeds of eco-innovation and knowledge exchange, finding novel ways to repurpose materials. Wider benefits include job creation in the circular economy (through new recycling or reuse enterprises) and enhanced materials security for industries (relying more on recovered materials reduces exposure to volatile raw material markets). [13]

Despite these benefits, several challenges and drawbacks are associated with implementing industrial symbiosis. One major challenge is regulatory barriers. Environmental regulations, while essential for safety and health, can inadvertently hinder IS when, for instance, a valuable by-product is legally classified as "waste" and thus cannot be easily transported or reused without special permits. Complex or unclear waste-handling rules have historically paralysed some resource exchanges. Recognising this, the EU has moved to clarify definitions of by-products and waste regulations to facilitate industrial symbiosis better [16]. Still, navigating compliance remains a hurdle: Companies must ensure that using another's waste meets all safety, quality, and legal standards, which can involve time-consuming approvals. Another set of barriers is economic feasibility. Not all potential synergies are financially viable; the costs of cleaning, processing, or transporting a by-product

may outweigh the savings from using it. For IS exchanges to make sense, there must be a net economic benefit or strategic gain.

In some cases, fluctuations in market prices (for raw materials or waste) can suddenly make a previously attractive exchange uneconomical. This ties into the challenge of long-term stability: if one partner in a symbiotic network shuts down or changes its output, the other partners may lose a key resource or outlet, potentially disrupting multiple linked processes. This dependency risk means companies can be hesitant to invest in modifications for symbiosis unless they are confident in their partners' reliability. [16–18]

There are also organisational and social challenges. [2, 17] Establishing symbiosis often requires a high degree of coordination and trust among entities that have no prior collaboration. Information barriers can prevent symbiosis opportunities from even being recognised – companies might simply not know that another nearby facility could use their waste. Overcoming this requires active networking and, sometimes, a facilitator to identify potential matches. Culturally, firms may be reluctant to rely on external partners for critical inputs due to fear of supply disruption, or they may guard proprietary information about their waste streams. Additionally, aligning the timing and quantity of exchanges can be complex: production processes must be synchronised to supply and receive the materials or energy in question consistently. Technical barriers can arise if waste material is not immediately suitable as an input and requires research and development (R&D) to repurpose it. Indeed, researchers categorise IS barriers as technical, economic, informational, regulatory, organisational, and even motivational. [17] For example, a lack of internal management support or the "not-invented-here" mentality can stymie cooperative efforts. Investment costs for necessary infrastructure (like pipelines for steam or water, storage facilities for materials) can be high upfront, posing a barrier, especially for small and medium enterprises. Finally, there may be cases of uneven benefit distribution – if one company gains significantly more than another from the exchange, it could lead to tensions in maintaining the collaboration. Thus, while industrial symbiosis carries tremendous upside, realising those gains requires overcoming a suite of regulatory, economic, and social challenges. Addressing these through supportive policies, facilitation, and good business planning is crucial to unlocking IS's full potential. [2, 19]

D. Industrial Symbiosis in the Papermaking Industry

Industrial Symbiosis has significant potential to enhance sustainability and improve resource efficiency in the paper and board industries. These industries are increasingly adopting IS practices, as demonstrated by specific examples of successful collaboration and resource maximisation. For instance, many paper mills have established networks with nearby companies to reuse cellulose fibres that were

previously considered waste by reintegrating those fibres back into their production processes. This cycle of resource recovery supports a circular approach to manufacturing, enhancing overall sustainability [20].

Another notable implementation of industrial symbiosis is the diversion of sludge produced during the papermaking process. Research indicates that sludge can often be repurposed or processed into alternative materials, such as bioenergy or compost, through partnerships with firms in different sectors, including agriculture and energy production [21]. The ability to convert waste into valuable products helps mitigate reliance on landfills, improve economic performance, and foster collaboration across industries.

The packaging sector within the paper industry is also witnessing the adoption of industrial symbiosis practices. Companies in this sector are increasingly collaborating with waste management firms to develop closed-loop systems that collect, recycle, and reintegrate discarded packaging materials into new production cycles. Through these practices, companies minimise their environmental impact and leverage the economic benefits of resource recovery [22, 23]. The European Union's push towards recycling and sustainability initiatives has further accelerated this trend, promoting the establishment of networks among various stakeholders.

Additionally, IS in the paper and board sectors benefits from technological advancements that facilitate data-sharing and optimise resource flow management. Digital platforms enable firms to monitor waste streams and connect with potential partners for resource exchange, streamlining the processes inherent in IS practices [24]. This technological integration supports more effective collaboration and enhances the efficiency of industrial symbiosis initiatives within the industry. [25]

However, challenges remain in promoting greater adoption of industrial symbiosis across the paper and board industries. Despite the recognised benefits, knowledge gaps persist, particularly among small and medium-sized enterprises (SMEs) that may lack the resources or expertise to engage in symbiotic practices. Furthermore, regulatory frameworks may not always encourage collaborative efforts, suggesting the need for more supportive policies to enhance IS initiatives [26].

Public awareness and education play crucial roles in overcoming these barriers. Engaging stakeholders in educational initiatives that emphasise the importance and benefits of IS can help inspire action and collaboration. This can include workshops, training programs, and partnerships with academic institutions focused on fostering innovation within IS frameworks. [27]

E. Current Implementation of Industrial Symbiosis in the Slovenian Papermaking Industry

In Slovenia, the paper and board industry is beginning to recognise the benefits of industrial symbiosis as a strategy for enhancing sustainability and resource

efficiency. Various initiatives and collaborations among companies indicate a positive shift toward implementing IS principles, yet significant potential for further development remains.

One notable implementation of industrial symbiosis in Slovenia can be found within the framework of local forestry and paper production. Slovenia, being one of the most forested countries in the European Union, has an abundance of biomass resources that can be utilised to produce paper and board products. Companies in the paper sector have collaborated with local sawmills and forestry companies to repurpose wood residues and by-products as raw materials for paper production. This collaboration reduces waste and enhances the sustainability of the supply chain by minimising the reliance on virgin fibres. The effective integration of waste from wood processing industries promotes a circular economy approach, where materials are reused rather than discarded. [28]

Moreover, the Slovenian government has initiated several programs to promote sustainable practices in the paper industry. These initiatives have encouraged the establishment of eco-industrial parks, where businesses can engage in symbiotic relationships. For example, cooperation between paper mills and recycling facilities enables the recycling of old paper and cardboard products, which are then transformed into pulp for new paper production. This practice reflects the core IS principle of turning waste from one process into a resource for another, thereby minimising environmental impacts and fostering resource recovery. [29]

The city of Celje has also emerged as a hub for industrial symbiosis within the paper industry, with several firms collaborating to share resources such as water and energy. Local paper mills have begun using treated wastewater from municipal treatment plants in their production processes. This exchange not only conserves fresh water resources but also highlights the potential for municipal-industrial collaborations that enhance sustainability in local economies. [30]

Nevertheless, several obstacles still impede the broader application of industrial symbiosis in Slovenia's paper and board industry. One significant barrier is the limited awareness of IS benefits among small and medium-sized enterprises (SMEs) in the industry. Many SMEs may lack the necessary knowledge and resources to explore collaborative opportunities [31]. Encouraging educational initiatives and providing guidance on implementing IS practices can empower these businesses to engage more actively in symbiotic relationships.

Moreover, regulatory and infrastructural challenges may hinder the establishment of efficient Industrial Symbiosis networks. For industrial symbiosis to flourish, comprehensive policies that incentivise resource sharing and collaboration among enterprises are essential. This necessitates a supportive framework that encourages organisations to minimise waste and optimise resource use while effectively addressing the complexities of forming partnerships. [32]

II. Case-Based Evidence of Industrial Symbiosis in the Pulp and Paper Sector

The pulp and paper industry is among Europe's most resource-intensive sectors, with high water and energy demands, and significant by-product streams, including sludge, bark, and ash. [33] These very features make it fertile ground for Industrial Symbiosis. By transforming unavoidable residues into new resources and linking mills to municipal or cross-sectoral partners, the sector has produced some of the most notable examples of symbiosis worldwide. [34]

This section draws on international flagship cases and a series of Slovenian examples. The aim is not to compile an exhaustive catalogue but to highlight characteristic modes of collaboration and to identify enabling conditions as well as persistent barriers. The exchanges were analysed across materials, energy, water, chemicals, and utilities, with each case mapped by governance, partner composition, and maturity level. While the majority of IS case studies originate in Europe, forest-based clusters in South America also demonstrate strong potential for circular integration. [35]

A. Large-Scale Industrial Ecosystems

In Northern and Western Europe, large pulp and paper companies have leveraged scale, infrastructure, and policy support to build extensive industrial ecosystems.

Metsä Group – Äänekoski Bioproduct Mill (Finland): A flagship bio-industrial hub where pulp production anchors a wider network of energy generation, chemical recovery, textile fibres, biogas, and fertilisers. The mill produces 1.3 million tonnes of pulp annually and generates about 240% of its own electricity needs, exporting roughly 1,000 GWh of electricity and 600 GWh of steam to external users. By-products include 46,000 tonnes of tall oil, 3,200 tonnes of turpentine, and 500 GWh of biofuels annually, and attracts on-site partners that valorise side streams. [7, 23, 36, 37]

UPM – Kaukas Integrated Site (Finland): A cluster combining a pulp and paper mill, sawmill, biorefinery, and CHP plant. Shared steam, electricity, bark, and black liquor flows illustrate deep resource integration, reinforced by UPM's corporate diversification into bio-based products. [7, 23, 38]

Stora Enso – Maxau Heat-to-City (Germany): A paper mill that pipes surplus biomass-based heat into Karlsruhe's district heating network, providing renewable energy to homes and public buildings. [7, 23, 39]

SCA Cluster Sites (Sweden): At Munksund, Obbola, and Östrand, SCA links pulp and paper mills with sawmills and cities, exchanging biomass, bark, and steam. Surplus heat supports municipal district heating. [7, 40, 41]

Kuusankoski/Kymijoki District (Finland): A historical eco-industrial network where mills and nearby companies share utilities, infrastructure, and by-products, creating a regional symbiosis model. [7, 42]

Santa Catarina Clusters (Brazil): A forest-based cluster where mills, sawmills, and thermoelectric plants burn wood residues and black liquor to generate renewable electricity for both industrial and municipal use. [35]

These cases show how industrial symbiosis becomes systemic when mills are embedded in wider industrial ecosystems, supported by scale and infrastructure such as CHP and district heating.

B. Mill-Level Circular Innovations

Beyond large ecosystems, several mills have pioneered specific circular practices that demonstrate replicability at smaller scales.

DS Smith – Kemsley (UK): The UK's largest recycled paper mill processes hard-to-recycle rejects, separating plastics and contaminants from fibre to boost recycling rates. CHP provides integrated energy. [43]

DS Smith – Lucca (Italy): Operates a fibre–plastic separation line that recovers usable fibres from mixed rejects while diverting plastics to recycling or energy recovery[44]

International Paper – Closed-Loop Packaging: Collects used corrugated boxes from customers, repulps them, and converts them into new packaging, closing the loop on fibre flows. [45]

Copelme S.A. (Bolivia): A pilot project exploring anaerobic digestion of wastewater sludge to produce renewable biogas for mill operations, cutting both emissions and fuel costs. [46]

These innovations highlight how even single-site mills can advance IS by valorising side streams, closing loops, and investing in recovery technologies.

C. Slovenian Cases

In Slovenia, symbiosis occurs at a smaller scale but provides distinctive models of municipal–industrial integration and cross-sector valorisation.

Paloma (Sladki Vrh): Operates a cogeneration plant that supplies both the mill and local households with heat, reinforcing the role of mills as pillars of community energy security. The district heating for Sladki Vrh and Vranji Vrh is supplied from Paloma's on-site boiler house with a 626 kW heat / 527 kW power CHP unit and a 1,500 kW peak hot-water boiler. The local DH network shows an average seasonal heat offtake of about 1,890 MWh, with 3,300 m of mains and 3,421 kW of connected capacity. [47–50]

Papirnica Vevče (Ljubljana): Pioneered integration of treated municipal wastewater into its production process, reducing freshwater extraction while easing the burden on public treatment systems. The on-site industrial WWTP treats approximately 800,000 m³ of process wastewater per year ($\approx$ 400 Olympic pools), meeting legal discharge parameters before release to the Ljubljanica. [51–53]

Papirnica Goričane (Medvode): Built a biological wastewater treatment plant, creating future opportunities for water reuse and sludge valorisation. In recent years, total freshwater use has been on the order of 1.3–1.4 million m³/year (e.g., 1.294 million m³ in 2024), with electricity consumption around 51,000–54,000 MWh/year and paper sludge generation fluctuating between 750 and 1,934 t/year. [54–56]

Radeče Papir Nova: Specialises in recycled paper pulp and has invested in reducing water, energy, and chemical consumption, showing gradual progress toward circular practices. [57]

VIPAP Videm Krško – PaperChain Project: Under the EU-funded PaperChain initiative, tested the use of paper deinking sludge in road construction, linking the pulp and paper sector with civil engineering. At full operation the mill has produced about 210,000 t/year of paper, generating large residue streams typical of deinking lines—approximately 67,000 t/year of deinking paper sludge (DPS) and 25,000 t/year of deinking paper sludge ash (DPSA)—which PaperChain targeted for replacement of virgin backfill in a $\sim$ 70 m railway section using 15 cm compacted layers. [7, 58–62]

Although modest compared to Nordic flagships, these Slovenian cases illustrate highly replicable pathways, especially in municipal–industrial cooperation and cross-sector material valorisation. [25]

D. Comparative Overview of Industrial Symbiosis Initiatives

Table 1 presents a cross-case comparison of industrial symbiosis initiatives in the pulp and paper sector. The table classifies each case according to its primary exchange dimensions, ranging from raw material supply and processing to energy integration, water reuse, by-product valorisation, and cross-sector linkages. The use of filled (●) and open (○) markers allows for a quick overview of which domains are most actively developed in each case.

Table 1. Process Flow of Industrial Symbiosis in the Pulp & Paper Sector

Case Study (Country)	Raw Material Supply & Processing	Energy Integration (CHP, Heat, Power)	Water Reuse / Treatment	By-product Valorisation (Materials, Chemicals)	Cross-sector Linkages (Municipal/ Constructi- on/etc.)
Metsä Äänekoski Bioproduct Mill (Finland)	●	●	●	●	●
UPM Kaukas Integrated Site (Finland)	●	●	○	●	●
Stora Enso Maxau (Germany)	○	●	○	●	●
SCA Sites – Munksund, Obbola, Östrand (Sweden)	○	●	○	●	●
Kuusankoski/ Kymijoki Cluster (Finland)	○	●	○	●	●
Santa Catarina Forest Cluster (Brazil)	●	●	○	●	●
DS Smith Kemsley (UK)	○	●	○	●	○
DS Smith Lucca (Italy)	○	●	○	●	○
International Paper (Closed-loop Packaging, USA/Europe)	●	●	○	●	○

Copelme S.A. (Bolivia)	○	● (biogas from sludge)	●	●	○
Paloma (Slovenia)	○	● (district heating)	○	○	●
Papirnica Vevče (Slovenia)	○	● (heat recovery)	● (municipal waste water reuse)	○	●
Papirnica Goričane (Slovenia)	○	○	● (biological wastewater treatment)	○	○
Radeče Papir Nova (Slovenia)	● (recycled paper)	○	● (water/energy savings)	○	○
VIPAP PaperChain (Slovenia)	○	○	○	● (sludge to construction)	●
DS Smith Slovenia (Slovenia)	○	●	○	● (fibre recovery, recycling)	○

Legend:

- = strong/active contribution
- = limited/indirect contribution

Table 1 shows that energy integration and by-product valorisation are the most consistently developed symbiosis exchanges across cases, particularly in Nordic ecosystems. In contrast, Slovenian mills demonstrate more modest but highly replicable linkages with municipalities, such as district heating and wastewater reuse. For example, Äänekoski exports more than 1,500 GWh of surplus energy each year, whereas Slovenian mills like Paloma focus on district heating at the municipal scale. This contrast illustrates how scale directly influences the type and magnitude of exchanges. On the Slovenian side, Vevče's ~800,000 m³/year of treated process water and Goričane's ~1.3 million m³/year of freshwater intake underscore that water management is the primary lever. Paloma's ~1.9 GWh/season district heating demand, by contrast, highlights community-scale heat integration rather than large energy exports.

E. Cross-Case Synthesis: Success Factors and Barriers

Examining the European and Slovenian cases, several success factors consistently emerge that help explain why certain industrial symbiosis initiatives thrive while others falter. The most obvious is geographic proximity. Mills embedded in industrial clusters or situated near cities benefit from the reduced costs and technical feasibility of exchanging energy, water, or materials. This explains why large complexes, such as Äänekoski in Finland or Kaukas in Lappeenranta, can integrate multiple facilities into a single functioning ecosystem, while Slovenian mills like Paloma and Vevče link directly to nearby municipal infrastructures. Without physical closeness, many of these exchanges would be unviable, particularly for heat and wastewater.

Another recurring factor is shared infrastructure and mutual economic benefits. Combined heat and power plants, wastewater treatment facilities, and transport pipelines all create opportunities for collaboration. These infrastructures only generate long-term value when partners see clear financial gains, whether through avoided costs, new revenue streams, or more secure supply chains. Paloma's ability to sell heat, Vevče's reduction of gas purchases, and Metsä's transformation of by-products into marketable products all illustrate that symbiosis succeeds when the economic case is evident for all sides. Projects without a compelling financial rationale, on the other hand, tend to remain pilot studies or collapse once external funding is withdrawn.

A third enabling condition is the role of champions and governance structures. Some of the most ambitious examples, such as Äänekoski or the PaperChain project, were made possible because corporate leaders or EU-funded consortia actively drove the process, reducing uncertainty and aligning diverse interests. In smaller-scale Slovenian cases, this role was often played by municipalities or external project partners who acted as facilitators. Strong governance reduces the "first-mover" risk that typically deters companies from experimenting with new forms of collaboration.

Supportive policies and regulatory frameworks also play a decisive role. The distinction between waste and by-product is a recurring bottleneck: whether sludge can be used in construction or whether treated wastewater can be reused depends not only on technical feasibility but also on legal classification. Where regulation is flexible and aligned with the objectives of a circular economy, projects move forward more easily. Conversely, rigid or unclear rules remain one of the most cited barriers, particularly in Slovenia, where smaller mills struggle to navigate regulatory requirements.

At the same time, the cases highlight a range of persistent barriers. Economic and market risks are among the most significant. High upfront investment, uncertain payback periods, and volatile secondary material markets all discourage

participation, especially among small and medium-sized mills that lack the capital reserves of larger Nordic companies. For small and medium-sized enterprises (SMEs), these constraints are particularly acute. Limited financial capacity, restricted access to expertise, and regulatory burdens mean that many SMEs cannot engage in industrial symbiosis without targeted support. Unlike large Nordic corporations, which can absorb infrastructure costs and risks, SMEs require tailored incentives, cooperative platforms, and technical assistance to make symbiosis viable. Organisational and cultural barriers also surface: companies are often reluctant to share sensitive data or depend on external partners, preferring self-sufficiency over collaboration. This is especially true in continuous processing industries, such as papermaking, where reliability is non-negotiable. If a symbiotic input cannot guarantee consistent quality and supply, mills are unlikely to take the risk. [35]

Finally, logistics and distance remain hard constraints. Heat cannot travel far without major losses, and transporting bulky or wet residues quickly erodes any economic advantage. Successful cases, therefore, tend to be hyper-local, reinforcing the importance of clustering and co-location. [35]

In summary, the comparative analysis reveals that while flagship ecosystems in Northern Europe benefit from scale, infrastructure, and corporate strategy, the Slovenian cases demonstrate the potential of municipal-industrial linkages and cross-sector valorisation in smaller economies. The conditions for success are clear and remarkably consistent across various contexts: proximity, infrastructure, economic benefits, governance, supportive policies, and trust. However, the barriers—regulatory complexity, economic risk, organisational inertia, and logistical limits—remain stubborn obstacles. Overcoming these challenges will require not only technological innovation but also regulatory reform, facilitation platforms, and a cultural shift toward collaboration and teamwork.

Figure 1 provides a comparative overview of the industrial symbiosis cases analysed, showing the distribution of exchange types (materials, energy, water, chemicals) across mills and clusters. The visualisation highlights that energy and material exchanges dominate the pulp and paper sector, with some flagship mills exporting more than 1,000 GWh of surplus energy annually. By contrast, water reuse and chemical recovery remain emerging areas, concentrated in large biorefinery projects such as Äänekoski and often requiring greater technological investment. Slovenian mills, meanwhile, manage water flows on the order of 10^5 – 10^6 m³ per year, reflecting their focus on community-scale symbiosis rather than large-scale energy exports.

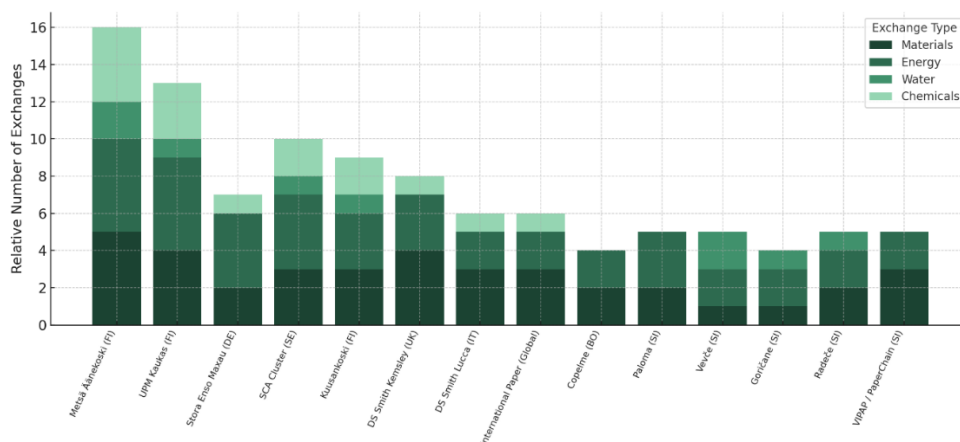


Fig. 1. Case Studies by Exchange Type

F. Recommendations

Drawing on international and Slovenian case studies, several recommendations can guide industry, policymakers, and researchers in strengthening industrial symbiosis, particularly in the pulp and paper sector.

For industry:

Start by mapping what goes in and out of production — from energy and water to waste streams and by-products. Very often, what appears to be "waste" can become a valuable input for a neighbor.

Build closer ties with municipalities and local businesses. District heating, wastewater treatment, or reusing sludge are all areas where cooperation can cut costs and reduce environmental burdens.

Pilot small projects first. Demonstrating exchanges such as water reuse or fiber recovery can work in practice, help to build trust and open the door to larger collaborations.

For policymakers:

- Simplify the rules around waste and by-products. Clear and consistent regulation reduces hesitation and makes companies more confident about trying new exchanges.
- Offer incentives that reward circular practices — for example, tax breaks, lower landfill fees, or dedicated funding for eco-industrial parks.
- Create spaces where companies from various sectors can meet, share information, and explore new opportunities for collaboration.

For researchers and facilitators:

- Develop tools and platforms that make it easier to match companies with complementary resource needs.
- Share good practices from pioneering projects, such as Kalundborg, but adapt them to the realities of local industries and communities.

- Keep track of IS initiatives over time and measure their impact, so that the benefits are visible and can be used to encourage further action.
For Slovenia in particular:
- Use smaller pulp and paper mills as hubs for collaboration. When connected with agriculture, energy providers, or local utilities, they can anchor regional symbiosis networks.
- Encourage clustering of companies in key regions to bring partners physically closer together and reduce the costs of exchange.
- Frame IS as part of Slovenia's larger shift toward a circular bioeconomy, positioning it as both an economic opportunity and an environmental necessity.

Taken together, these recommendations suggest that industrial symbiosis is not just a technical fix but a way of working differently — one that relies on trust, cooperation, and a willingness to see waste as a resource. If these conditions are met, the pulp and paper sector in Slovenia, and elsewhere, can play a leading role in building a more circular and sustainable economy.

III. Conclusion

The evidence from European and Slovenian pulp and paper mills underscores the sector's crucial role in advancing industrial symbiosis as part of the broader circular and low-carbon transition. Traditionally viewed as a resource-intensive industry, pulp and paper is increasingly turning its challenges into opportunities - exchanging energy, reusing water, and finding new value in by-products.

Flagship bioproduct mills in Northern Europe, such as Metsä Äänekoski and UPM Kaukas, demonstrate what can be achieved when scale, corporate strategy, and infrastructure align. The Äänekoski site alone produces over 1.3 million tonnes of pulp per year and exports around 1,600 GWh of surplus energy to regional grids. These sites have evolved into regional innovation hubs, linking pulp production with energy, chemical recovery, textile fibres, and fertilisers. At the same time, Slovenian cases remind us that industrial symbiosis is not limited to large-scale projects. Paloma, Papirnica Vevče, and VIPAP demonstrate that smaller mills, when working closely with municipalities and partners, can also deliver meaningful innovations — such as cogeneration for community heating, water reuse, and road-building materials derived from paper sludge.

Across all these examples, some common threads stand out: proximity and cooperation, strong governance, and the role of pilot projects in lowering financial risks. At the same time, persistent challenges remain, especially around restrictive waste regulations, volatile secondary markets, and the limited resources of smaller mills. These barriers highlight the importance of policy frameworks that can adapt,

incentivise collaboration, and provide support for small and medium-sized enterprises.

Looking ahead, the pulp and paper industry has the chance to define itself not only as a producer of fibre, but also as an anchor of local industrial communities and a driver of circular innovation. By embedding IS practices into large bioproduct clusters and smaller regional networks, the sector can make a tangible contribution to the goals of the European Green Deal: improving resource efficiency, achieving carbon neutrality, and building climate resilience.

Ultimately, this study demonstrates that industrial symbiosis in the pulp and paper sector is not an abstract concept, but a practical pathway that is already delivering results. With the right support and wider adoption, it can transform the industry's role in shaping a more sustainable and resilient future for Europe and beyond.

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THE WASTE MANAGEMENT IMPACT: PATHWAYS TOWARD SUSTAINABLE MANAGEMENT IN SAMARKAND

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Abstract

The article examines the main issues associated with industrial waste and household waste management. The rapid growth of urbanization and human activity in recent years has negatively impacted the ecological situation in the Samarkand region. Based on statistical datasets, field investigations, and an analysis of the regulatory framework, the study reveals that waste volumes are rapidly increasing while recycling and treatment rates remain critically insufficient. Improper disposal practices, including open dumping and uncontrolled incineration, have been shown to significantly contribute to health problems within the population. The findings strongly demonstrate that, without systemic reforms, waste accumulation will continue to exacerbate environmental degradation and health risks. However, the study confirms that sustainable management through mandatory waste separation, the expansion of recycling infrastructure, the controlled disposal of hazardous materials and the adoption of innovative eco-technologies can substantially mitigate these adverse outcomes.

Keywords

sustainability; waste management; household waste; industrial waste; public health.

I. Introduction

In recent years, Uzbekistan has generated more than 100 million tons of industrial and per year (14% of which is toxic waste), about 35 million tons of household waste. Considering that landfills and waste storage facilities store about 2 billion tons of industrial, construction, and household waste and occupy an area of 12 thousand hectares, it is not difficult to imagine the negative impact of waste. Environmental protection from production and consumption waste is inextricably linked with the problems of rational use of natural resources and the introduction of environmentally friendly technologies. For many centuries, improper waste management has led to changes in natural resources, unexpected changes in nature, but this situation is changing thanks to the new regulations [1-3]. There are studies that emphasize the role of sustainable waste management, as well as the potential of composting strategies in developing cities to reduce landfill pressure [4].

Moreover, medical waste poses a danger not only of direct but also indirect spread of infectious and non-communicable diseases among the population due to pollution of the environment and almost all its elements - water, air, soil, food, and all this requires a serious environmental approach to this problem. In addition, 80% of these wastes are organic substances, and when they are processed in a sustainable and circular way, a large amount of energy and energy carriers can be obtained [5,6].

The main goal of waste management policy is to prevent environmental pollution and protect public health by reducing waste generation and improving recycling practices. In Uzbekistan, the 2002 Waste Law regulates waste management and establishes standards for minimizing harmful effects on health and the environment [2,3,7,8]. Key objectives include:

- Preventing toxic pollution from industrial and medical waste.
- Expanding waste collection and recycling systems.
- Encouraging foreign investment in recycling industries.
- Promoting modern waste-free and low-waste technologies.

However, current legislation does not adequately regulate medical waste, the Ministry of Health is working on the elimination and neutralization of medical waste.

II. Material and methods

This study was conducted to investigate the environmental and public health impacts of industrial waste and household waste across Samarkand and its surrounding districts. A combined methodological approach was employed, incorporating statistical data analysis, field observations and a review of existing regulatory frameworks.

Statistical data on waste generation, recycling and disposal practices have been obtained from national and regional environmental agencies, health departments and publicly available international databases. To assess the regulatory context and medical implications of waste management, official records from the Ministry of Health and the State Committee for Ecology and Environmental Protection of Uzbekistan were also consulted.

A. Data Collection and Processing

Table 1. Data Collection and Processing

Category	Explanation
Waste characterization	industrial, household, agricultural, construction and medical waste were categorized according to international classification standards and national legislation. Hazard classes were identified using both the Federal Classification Catalogue of Waste (FCCW) and Uzbek standards.
Health indicators	Morbidity rates were collected from official health statistics for various districts of Samarkand. Particular focus was given to diseases associated with environmental pollution, such as respiratory.
Environmental monitoring	Reports on the quality of the air, water and soil were reviewed to identify any correlations between waste accumulation and ecological degradation.

B. Limitations

The study relied primarily on secondary statistical data and reports from government and international organizations. Due to limited access to raw field data, it was not possible to quantify some correlations between waste and health outcomes with precision. Nevertheless, combining multiple data sources and using international classification standards allowed for a comprehensive evaluation of the situation.

III. Results and discussions

The industrial and household waste impacts the environment and public health. This section presents the analysis results, focusing on the diversity of waste sources, the classification system used in Uzbekistan, and the environmental and health risks associated with improper waste management. Particular attention is paid to the role

of recycling and innovative technologies in reducing the harmful effects of waste, as well as to the importance of developing effective strategies for sustainable waste management.

A. Waste characterization

Waste classification systems are established by legislation to ensure a systematic approach to environmental protection and public health. According to the legislation of the Republic of Uzbekistan on waste [2], waste is divided into groups according to the source of generation, physical state and recycling potential. Waste is also classified according to the level of danger it poses to the ecosystem.

Regardless of the origin, all waste is classified to minimize its harm to the environment, as well as to create optimal sanitary conditions to prevent the spread of viruses, infections and other pathogenic microorganisms.

Furthermore, waste is categorized according to the degree of hazard it poses to ecosystems. In 2003, the Government of the Russian Federation approved the Federal Waste Classification Catalogue (FWCC), which contains a comprehensive register of waste types, their properties, and associated hazard classes [9].

Table 2. The nature of the origin waste according to FWCC, adapted by authors

Waste type	Description/ Explanation
Chemical	Substances or a complex of substances that have been obtained in chemical laboratories or factories. Such waste can harm human health and disrupt the ecological balance. Chemical wastes such as mercury, alkali, acids, solvents, pesticides, oils and electrolytes are most common
Mineral	This category includes products with minerals in their composition that have expired or have been damaged. Such waste usually occurs as a result of the mining and glass working industries, as well as in the manufacture of fertilizers and building materials.
Organic	This is garbage that can decompose independently and release nutrients. This category includes missing food products, as well as animal and human waste.
Communal	Residues of consumer or industrial products that have lost their properties during use. These include packaging, furniture, equipment and tools. All these wastes arise from the activities of industrial enterprises and humans. Types of waste. The aggregate state is one of the criteria for classifying waste, which helps determine how they are stored and transported. Waste can be: solid, liquid, pasty, gel-like, etc.

The Federal Waste Classification Catalogue is a comprehensive framework that systematically categorizes waste based on their degree of danger. This classification is recognized as a standardized method for the identification of hazardous waste, which divides waste into five distinct hazard classes, ranging from low to high risk, based on their potential to cause harm to the ecosystem, as reported in Table 3.

Table 3. Hazard classes of garbage according to the degree of their harmful effects on the ecosystem, adapted by the authors

Hazard classes	Description
Class I Extremely hazardous	mercury-containing instruments, lamps, and transformers.
Class II Highly hazardous	chemical waste, batteries, tyres, acidic/alkaline solutions.
Class III Moderately hazardous	petroleum products, cement dust, and agricultural residues.
Class IV Low-hazard	glass, furniture, tyres, bitumen, decomposing within 3 years.
Class V Practically non-hazardous	minimal ecological impact, quick decomposition.

A separate classification of waste is medical waste, regulated by SanPiN and classified into: safe, epidemiologically hazardous, extremely hazardous, toxicologically hazardous, and radioactive [10]. Proper collection, sorting, and disposal of medical waste are crucial to prevent contamination and the spread of disease [11].

B. Environmental and health impacts

Waste production and management can significantly impact both the environment and human health if not properly handled. For example [12,13]:

Table 4. Examples of good practices regarding waste management

Direction	Description
Landfills	could release methane and toxic leachates, contaminating air, soil, and water.
Waste incineration	could produce harmful gases containing cadmium, mercury, and lead.
Plastics	persist in the natural environment for hundreds of years and degrade only slowly, leading to the accumulation of

Direction	Description
	microplastics in soil and aquatic ecosystems. Batteries, electronic waste, and used tyres release heavy metals and toxic compounds, creating significant ecological risks and serious consequences for human health

According to national and international statistics, each urban resident generates an average of 500-800 kilograms of municipal solid waste per year [14]. A substantial portion of this waste can be regarded as secondary raw material suitable for recycling and reuse; however, in practice, the recycling rate remains relatively low.

Uzbekistan generates approximately 4 million tons of MSW annually, with projections indicating an increase to 7 million tons by 2030. Additionally, the country produces 100 million tons of industrial waste [15].

Therefore, strengthening systems for waste separation and recycling is a key condition for ensuring environmental sustainability and protecting public health, while education for sustainable development plays a vital role in raising awareness, fostering responsible behaviour, and empowering communities to actively participate in sustainable waste management practices [16-18].

To provide a clearer overview of the environmental and health implications of different waste types, a summary is presented below (Table 5).

Table 5. Selected waste types and their environmental and health impacts

Waste type	Environmental impact	Health risks	Indicator
Plastics	Decompose over 100–400 years, generating microplastics	Adverse effects on the respiratory and digestive systems	Very slow degradation
Batteries	Release of lead, cadmium, mercury	Nervous system and kidney diseases	Classified as hazardous waste
Electronic waste	Contains heavy metals and toxic substances	Respiratory diseases, cancer	~50 million tons/year globally
Tires	Decompose slowly, release toxic compounds	Allergies, respiratory illnesses	Tens of millions of tons/year
Municipal waste	Accumulates in landfills, with low recycling rates	Risk of infectious diseases	500–800 kg/person/year

The severity of the impact of waste treatment and disposal on the environment and public health depends on the volume of waste produced, its composition, the amount of illegally buried waste, the amount of waste disposed of in landfills and the standards at waste treatment plants. The future impact of the waste management process will depend on how these factors change. The final treatment of waste, today, means either their burial in a landfill or incineration, and these two types of final treatment have different, but in both cases negative, effects on the environment and public health. In Table 6 data about public health (anaemia) are reported.

Table 6. The number of people suffering from anaemia in cities and districts of the Samarkand region (compared to 100,000 people)

Cities and districts	2021	2022	2023	2024
Samarkand	147040	143165	146032	144194
Kattakurgan	10625	11244	11326	10985
Surgut district	33171	49442	47525	39623
Samarkand district	43335	35652	34956	38022
Tailyak district	45658	39847	41256	43212
Bulungur district	15226	16425	17023	19366
Dzhamboiskiy district	25432	25057	24856	21412
Akdarya district	20991	22763	23666	26332
Payaryk district	25494	33762	29658	31855
Ishtikhansky district	33889	18931	21332	22432
Pastdargom district	49411	53198	55656	54003
Nurabad district	14051	23517	18802	16089
Kattakurgan district	46862	50332	49856	42362
Kushrabad district	21892	23361	23998	22698
Narpai district	20610	20543	21056	25213
Pakhtachi district	15862	25448	24099	26658

More and more hazardous waste that used to be placed in landfills is now being collected and processed properly, but not all of them. For example, in Samarkand, used electrical and electronics apparatus (televisions, refrigerators, etc.) continue to be taken to the landfill, although harmful substances are present in them. Old landfills contain a large amount of harmful waste and toxic chemicals that have been placed on them for years and have penetrated the environment. Since toxic waste

poses a significant danger to the environment, including human health, its management should be carried out in strict accordance with existing rules and standards [19].

The toxicity of heavy metals and their effect on a warm-blooded organism have been studied [20]. It is known that when ingested, they can affect the function of haematopoiesis, cause changes in the morphological composition of peripheral blood, block sulfhydryl groups, and pose a danger, contributing to the development of carcinogenic, genetic, and other long-term biological effects.

Biochemical decomposition and chemical oxidation of landfill material can be accompanied by spontaneous combustion of waste [20]. In Table 7, some data are reported within the Shahar and the districts.

Table 7. External causes and general morbidity rates in 2023

Name of Shahar and the districts of the Samarkand Region	2023 r			
	Whole	Children under 14 years old	A teenager aged 15-17 years old	Adults
Bulungur district	0	0	0	0
Jambai district	0	0	0	0
Kattakurgan district	6422	1724	1287	3411
of Kattakurgan	0			
Kushrabad district	0	0	0	0
Narpai district	0	0	0	0
Akdarya district	0	0	0	0
Payaryk district	0	0	0	0
Pastdargom district	0	0	0	0
Pakhtachi district	1287	0	1287	0
of Samarkand	1307	81	5	1221
Samarkand district	0	0	0	0
Tailyak district	0	0	0	0
Urgut district	0	0	0	0
Ishtikhansky district	15892	2048	1035	12809
Nurabad district	0	0	0	0
By region:	24908	3853	3614	17441

During the investigation on waste management, the following main violations were identified: no fence around the waste disposal facility; isolation of the disposed

waste is not carried out; laboratory control of the landfills emissions is not carried out; a disinfectant barrier is not used.

The use of waste as raw materials makes it possible to use natural resources more efficiently and reduce harmful emissions into the atmosphere and wastewater discharges. For example, using wastepaper as a raw material to produce new paper, can reduce harmful emissions into the air by 70-80%, and the pollution of water bodies by 30-35%, compared with the use of primary raw materials [21]. About four cubic meters of wood can be saved by using one ton of waste paper. Thus, thousands of hectares of forest land are preserved, which, in turn, help purify the atmosphere of carbon dioxide.

Eco-wool, a thermal insulation material made from wastepaper, has been produced for many years and represents an ecological solution that is safe for both humans and the environment [22].

With the growth of the automotive industry, environmental impacts have increased. In addition to batteries, plastics, and metal, cars emit a huge amount of waste, particulate matter, microplastics, etc., from the rubber tyres [23,24]. In Samarkand, the majority of waste is disposed of in landfills, with only about 3–4% being recycled, reflecting a significant shortage of recycling facilities, while the existing combustors merely transform one type of waste into another rather than providing a sustainable solution [25,28].

C. Recycling and Innovation

Recycling and innovative approaches to waste treatment play a decisive role in reducing the ecological and health impacts of industrial and household waste. Proper implementation of these methods helps to conserve natural resources, minimize landfilling, and reduce pollutant emissions [29,30].

Recyclable Waste. Most categories of waste can be recycled, which helps to reduce the growth of landfills and conserve natural resources. Waste can generally be divided into two main groups: waste suitable for the production of recyclable materials, and waste suitable for reuse in industrial production. Although recycling requires financial investment, it is economically beneficial in the long term because it produces secondary raw materials.

Waste Treatment and Cleaning. Waste cleaning involves a combination of recycling, treatment, and disposal. Each method has its own purpose:

- Recycling transforms waste into new products, reducing the volume of material sent to landfills.
- Treatment is especially important for hazardous waste, as it reduces its harmful properties before disposal.
- Disposal is used as a last resort when recycling or treatment is not feasible, ensuring safe containment of waste.

The most effective cleaning strategy depends on the type and quantity of waste produced. Recycling is best suited for non-hazardous waste, while treatment is necessary for hazardous materials to reduce environmental and health risks. Disposal should only be used as a last resort for waste that cannot be recycled or treated. The choice between recycling, treatment, and disposal must therefore be carefully adapted to the specific characteristics of the waste in question.

IV. Conclusions

The analysis of waste management approaches allows us to draw several important conclusions and recommendations. Effective waste management requires coordinated efforts from authorities, specialized organizations, and the population.

A. Recommendations for Authorities and Organizations

- Establish collection points for household and industrial waste, as well as recycling facilities, with mandatory licensing for hazardous waste management.
- Define clear regulations for organizations engaged in the disposal and processing of hazardous and non-hazardous waste.
- Organise a selective collection of solid waste and ensure its reuse in economic circulation as an additional source of raw materials.
- Create specialized municipal services for the removal of solid and liquid household waste, ensuring proper licensing for hazardous waste management.
- In areas without municipal waste removal services, local governments should conclude contracts with licensed specialized enterprises or individual entrepreneurs.
- Set deadlines for household waste removal, approve tariffs for waste management services, and provide payment benefits for socially vulnerable groups.
- Conduct regular activities aimed at eliminating unauthorized landfills and preventing their reappearance.
- Develop properly designed landfills with subsequent reclamation of existing authorized disposal sites.

B. Recommendations for the Population

- Practice separate collection of household waste such as textiles, glass, paper, and plastics by using labelled containers or delivering materials to specialized enterprises.
- Follow proper waste disposal practices, avoid polluting the environment, and educate children on responsible waste management.

- Be aware of hazardous household waste, such as mercury lamps and used batteries, which require special storage, collection, and disposal conditions.
- Avoid storing household waste, especially hazardous types, inside dwellings, as improper storage may result in administrative measures.
- Refrain from unauthorized burial or incineration of waste, as these practices pollute the environment and harm public health.

Overall, sustainable waste management requires a balance between recycling, treatment, and safe disposal, supported by clear regulations and public awareness. Authorities must ensure an effective infrastructure for waste collection and processing, while the population should take an active role in reducing waste generation and practicing environmentally responsible behaviour. Only through joint responsibility can society minimize the negative impact of waste on the environment and human health, while moving toward sustainable development.

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STRATEGIC INNOVATION MANAGEMENT IN THE CONTEXT OF INTELLIGENT MECHATRONIC SYSTEMS: AN INTEGRATIVE APPROACH TO BUSINESS PROCESS TRANSFORMATION IN THE AUTOMOTIVE INDUSTRY

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Abstract

This research investigates the strategic integration of artificial intelligence into mechatronic systems and its transformative impact on innovation, operations, and organizational leadership. Focusing on the automotive industry, it highlights how intelligent systems enhance adaptability, efficiency, and decision-making across business functions. The study emphasizes that successful implementation requires more than technological advancement — it demands strategic alignment, cultural readiness, and effective governance. By bridging technical innovation with managerial insight, the work offers a comprehensive perspective on how AI-driven mechatronics is reshaping the future of enterprise transformation in an increasingly digital and dynamic environment.

Keywords

Artificial Intelligence; mechatronic systems; strategic innovation; digital transformation; organizational agility.

I. Introduction

The automotive industry is experiencing a major transformation, mainly due to the integration of intelligent mechatronic systems and artificial intelligence (AI). This technological synergy is not only redefining the functional capabilities of modern vehicles but also prompting a strategic reorientation among automotive manufacturers. Intelligent mechatronic systems, which integrate mechanical, electronic, and software elements, now play a central role in advancing vehicle

performance, safety, and adaptability. But how does the integration of intelligent mechatronic systems and artificial intelligence influence strategic and operational transformation processes in the automotive industry?

The integration of these systems significantly contributes to enhancing performance and operational efficiency by enabling real-time data analysis, implementing advanced predictive maintenance strategies, and automating the decision-making process within the mechatronic system's operation. Figure 1 illustrates how the integration of AI and mechatronics functions within the broader automotive value chain, highlighting their combined impact across key areas such as design, manufacturing, and user experience.

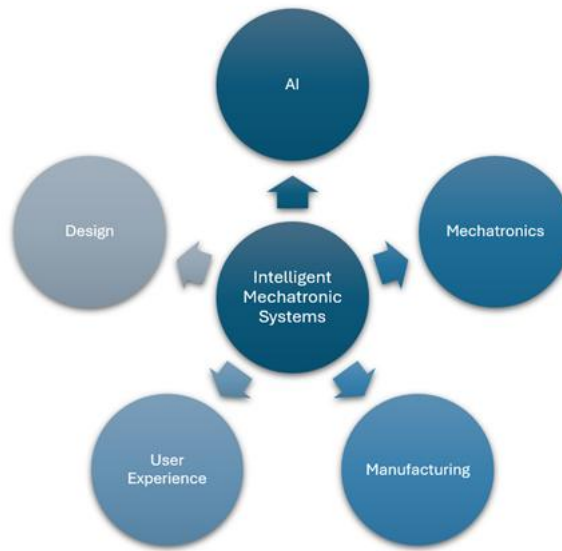


Fig. 1. AI and mechatronics in the automotive value chain

This transformation is driven by rising consumer expectations for vehicles that are not only efficient and safe, but also capable of adaptive responsiveness

to user needs. Features like lane-keeping assistance, adaptive cruise control, and real-time diagnostics are now considered standard rather than exceptional. In response, automotive firms are significantly increasing their investment in research and development to embed AI-enhanced mechatronic systems across their product offerings [1].

This article investigates the strategic innovation management practices that support the integration of these advanced technologies within the automotive industry. It aims to examine how AI and mechatronic systems are reshaping organizational processes and to identify the managerial strategies required to navigate this evolving landscape. Through an analysis of current industry trends,

case studies, and relevant theoretical models, the study seeks to offer practical insights into managing innovation effectively in this context.

This research aims to support automotive companies in managing the challenges of technological integration. It provides a conceptual framework to guide the understanding, planning, and implementation of AI-based and intelligent mechatronic solutions. As the industry moves toward increasingly autonomous and intelligent vehicles, the ability to strategically manage innovation becomes an important success factor [2]. Well-executed innovation management can enhance operational efficiency, elevate customer satisfaction, and strengthen competitive positioning.

This research also enhances the larger conversation on strategic management concerning technological innovation. It highlights the necessity of aligning technological initiatives with organizational goals and emphasizes the importance of a unified strategy that integrates technology, processes, and human resources [3].

Recent industry analyses underscore the urgency and complexity of this shift. For instance, a McKinsey report highlights how the convergence of artificial intelligence (AI), connectivity, and automation is redefining the automotive value chain, compelling manufacturers to adopt more agile and innovation-driven business models [4]. Similarly, Deloitte's insights into smart manufacturing emphasize the need for robust innovation governance and cultural readiness to navigate the challenges of digital transformation [5].

Based on all of the above, it can be stated that the integration of intelligent mechatronic systems and AI presents both significant opportunities and complex challenges. Strategic innovation management emerges as a crucial framework for guiding firms through this transition, ensuring that technological progress translates into sustainable business value.

II. The role of intelligent mechatronic systems in automotive innovation

The automotive sector is undergoing a major transformation, fueled by the growing integration of mechanical systems, electronic components, and advanced software—an interdisciplinary approach often referred to as mechatronics. These systems are not merely technological enhancements; they represent a strategic transformation in how vehicles are designed, manufactured, and experienced.

At its core, an intelligent mechatronic system is a synergistic integration of mechanical components, electronic control units (ECUs), and embedded software that collectively enable adaptive, responsive, and often autonomous functionalities. Unlike traditional systems that operate based on pre-programmed logic, IMS can process real-time data, learn from it, and make decisions accordingly. This capability is particularly crucial in modern vehicles, where responsiveness to dynamic driving conditions is essential for both safety and performance.

One of the most prominent applications of IMS in the automotive industry is in Advanced Driver Assistance Systems (ADAS). These systems rely on a cameras, network of sensors, and control units to assist the driver in real-time and monitor the vehicle's surroundings. Features like lane-keeping assistance, adaptive cruise control, and automatic emergency braking are supported by advanced mechatronic systems. These systems improve safety, reduce driver fatigue, and enhance driving comfort. Figure 2 illustrates the main functional domains where AI-driven intelligent mechatronic systems are currently applied in the automotive industry, highlighting their relative impact and strategic importance.

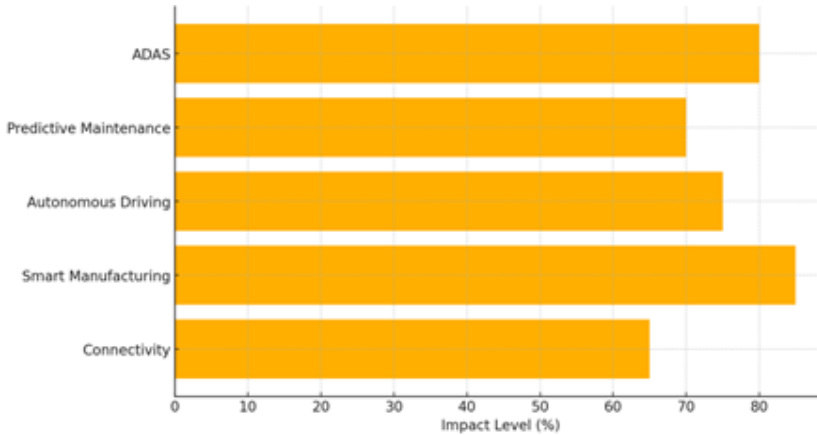


Fig. 2. Functional applications of intelligent mechatronics in the automotive industry

The integration of AI into mechatronic systems significantly amplifies their capabilities. Artificial intelligence (AI) algorithms play a key role in enabling predictive analytics within modern vehicles. By continuously analyzing data from various embedded sensors, these systems can detect early signs of wear or malfunction. For instance, vibration patterns from the engine or temperature fluctuations in the braking system can be monitored to forecast potential issues. This allows for timely maintenance interventions before failures occur, helping to minimize vehicle downtime and reduce overall maintenance costs [6].

Moreover, AI-driven IMS are central to the development of autonomous vehicles. These systems must interpret vast amounts of data from LiDAR, radar, and vision sensors to make split-second decisions. The complexity of this task requires not only robust hardware but also sophisticated software capable of deep learning and real-time processing.

In addition to enhancing vehicle functionality, IMS are transforming automotive manufacturing. AI-powered robotics and automation systems are now commonplace on production lines, where they perform tasks ranging from welding

and painting to quality inspection. Vision systems equipped with AI can detect minute defects in components, ensuring high standards of quality control. This level of precision is difficult to achieve with human inspection alone and contributes to greater efficiency and consistency in manufacturing processes [7].

The shift toward electrification in the automotive industry further underscores the importance of IMS. Electric vehicles (EVs) require sophisticated systems to manage battery performance, energy efficiency, and regenerative braking. Intelligent mechatronic systems play a crucial role in optimizing these functions. For instance, thermal management systems in EVs use IMS to regulate battery temperature, ensuring optimal performance and longevity.

Another major trend is the connectivity of vehicles. Modern vehicles are increasingly connected to external networks, allowing features like remote diagnostics, real-time traffic updates, and over-the-air software updates. IMS facilitate this connectivity by managing the flow of data between the vehicle and external systems. This capability not only enhances the user experience but also opens new avenues for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, which are essential for the development of smart transportation systems.

Customization is also becoming a key differentiator in the automotive market. Consumers now expect vehicles to adapt to their preferences, from seat positions and climate control settings to infotainment options. IMS enable this level of personalization by learning from user behavior and adjusting system parameters accordingly. For example, Toyota's "Yui" system uses AI to understand driver emotions and tailor the driving experience to their mood and preferences [8].

Despite their numerous advantages, the implementation of IMS is not without challenges. One of the primary concerns is system complexity. As more functionalities are integrated into a single system, ensuring reliability and safety becomes increasingly difficult. This complexity necessitates rigorous testing and validation processes, as well as robust fault-tolerant design strategies.

Cost is a major barrier for developing and deploying intelligent mechatronic systems, requiring significant investments in research, development, and infrastructure. While the long-term benefits, like improved safety and reduced maintenance, are valuable, these costs can affect vehicle affordability, especially in price-sensitive markets [9].

Regulatory compliance is a vital concern for manufacturers of Information Management Systems (IMS). Since these systems often collect and process personal data, it is essential for manufacturers to comply with data privacy laws, such as the General Data Protection Regulation (GDPR) in the European Union. Additionally, safety standards for autonomous and semi-autonomous systems are still evolving, requiring ongoing collaboration between industry stakeholders and regulatory bodies [10].

Intelligent mechatronic systems, especially when integrated with AI, are revolutionizing the automotive industry. They enhance vehicle performance, improve safety, streamline manufacturing, and offer personalized user experiences. To reach their full potential, major challenges regarding complexity, cost, and regulation need to be addressed. As the industry continues to evolve, sustained investment in research and development, along with cross-disciplinary collaboration, will be essential. Intelligent technologies are becoming increasingly important in shaping the future of mobility, with mechatronic systems playing a key role in this transformation.

III. Strategic innovation management: concepts and relevance

In today's fast-changing business environment, innovation is a strategic necessity. As organizations face mounting pressure from technological disruption, shifting consumer expectations, and global competition, the ability to manage innovation strategically has become a defining factor for long-term success. Strategic Innovation Management (SIM) is a focused and systematic approach to promoting innovation in alignment with an organization's overall goals and transformation strategy.

A. Theoretical foundations and frameworks

Strategic Innovation Management draws upon a rich tapestry of theories from strategic management, organizational behavior, and innovation studies. One of the foundational frameworks is the Resource-Based View (RBV), which posits that firms gain competitive advantage by leveraging unique, valuable, and inimitable resources, innovation capabilities being among the most critical. According to this view, innovation is not merely about generating new ideas but about embedding innovation into the firm's core competencies and routines.

The Dynamic Capabilities Theory emphasizes a company's ability to adapt and evolve by updating its internal and external skills in response to change, an essential trait in today's fast-paced digital environment. Similarly, the Ambidexterity Framework highlights the need for organizations to balance innovation (exploring new ideas) with efficiency (improving existing processes). Companies that manage this balance effectively are better equipped to innovate while maintaining strong operations. Figure 3 visualizes the relative conceptual influence of the three foundational theories, Resource-Based View, Dynamic Capabilities, and Organizational Ambidexterity, on Strategic Innovation Management, emphasizing their complementary roles in guiding innovation strategy.

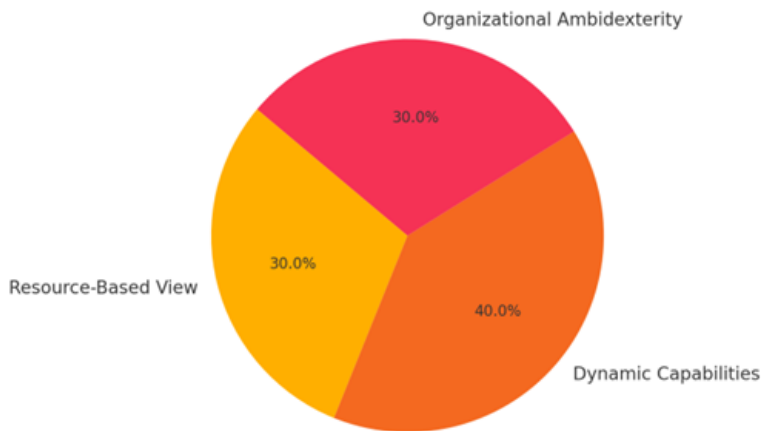


Fig. 3. Strategic frameworks supporting innovation

Figure 3 provides a visual representation of the relative conceptual influence of these three frameworks on SIM. The pie chart is divided into three segments, each corresponding to one of the theories. Dynamic Capabilities occupy the largest portion at 40%, followed by Resource-Based View and Organizational Ambidexterity, each contributing 30%. This distribution underscores the complementary nature of these frameworks in shaping innovation strategy.

Together, these three frameworks form a robust conceptual foundation for Strategic Innovation Management. The visual representation in Figure 3 not only quantifies their influence but also emphasizes their interdependence. By integrating the strengths of Resource-Based View, Dynamic Capabilities, and Organizational Ambidexterity, firms can craft innovation strategies that are both visionary and grounded, adaptive yet efficient.

B. Innovation as a strategic capability

When managed strategically, innovation becomes a core capability rather than a series of isolated efforts. This shift requires a cultural and leadership mindset where innovation is embedded in the organization's vision and daily practices. Key elements of strategic innovation capability include anticipating future technologies, fostering continuous learning, building strong internal and external collaborations, and ensuring leadership actively supports and drives innovation.

The integration of digital technologies has further elevated the strategic importance of innovation. As Zare and Persaud highlight, digital transformation is not just about adopting new tools but about rethinking business models and value creation mechanisms [11]. Firms that treat digital innovation as a strategic capability are better equipped to navigate disruption and seize new opportunities.

C. Aligning innovation with business transformation

One of the most critical aspects of Strategic Innovation Management is its alignment with business transformation. Innovation efforts that are disconnected from the organization's strategic direction often fail to deliver meaningful impact. Conversely, when innovation is tightly aligned with transformation goals, it becomes a powerful enabler of change.

Business transformation typically involves reimagining core processes, structures, and value propositions to achieve significant performance improvements. In this context, innovation serves as both a catalyst and a vehicle for transformation. For example, the adoption of AI-driven mechatronic systems in the automotive industry is not merely a technological upgrade but a strategic move to redefine mobility, customer experience, and operational efficiency.

The alignment process begins with strategic intent, a clear articulation of where the organization wants to go and how innovation will help it get there. This intent must be translated into innovation portfolios that balance short-term improvements with long-term breakthroughs. According to Siano Rêgo et al., successful alignment also requires robust governance structures that ensure innovation initiatives are evaluated, prioritized, and integrated into the broader transformation roadmap [12].

D. Challenges and Opportunities

Strategic innovation management offers considerable advantages, but it also presents complex challenges. One persistent issue is the innovation paradox: organizations often commit significant resources to innovation efforts without achieving the expected outcomes. This disconnect is frequently rooted in vague strategic priorities, inconsistent execution, or cultural resistance to change.

Organizational inertia often hinders innovation, especially in established firms resistant to change. Overcoming this requires strong leadership, a clear vision, and a culture that supports experimentation and learning from failure. At the same time, emerging digital technologies, like AI, IoT, and big data, offer new opportunities for strategic innovation by enabling agility, personalization, and novel business models.

Sustainability and social responsibility are also reshaping innovation priorities. Companies are increasingly using innovation to address global challenges such as climate change and inequality, which not only enhances their reputation but also opens new paths for growth.

In today's fast-changing environment, strategic innovation is essential. When guided by sound theory and aligned with transformation goals, it becomes a key driver of resilience, adaptability, and long-term success.

IV. Business process transformation through AI-driven mechatronics

The incorporation of artificial intelligence (AI) into mechatronic systems is not only transforming the design and functionality of modern vehicles but also driving significant changes in business processes across the automotive industry and beyond. As organizations strive for greater efficiency, agility, and innovation, AI-driven mechatronics has emerged as a strategic enabler of digital transformation.

A. The impact of mechatronic systems on business processes

At the heart of AI-driven mechatronics lies the convergence of mechanical engineering, electronics, and intelligent software. These systems are capable of sensing, processing, and acting upon data in real time, enabling a level of responsiveness and adaptability that traditional systems cannot match. In business contexts, this translates into more streamlined operations, predictive capabilities, and enhanced product and service offerings.

AI-driven mechatronic systems significantly automate complex tasks, such as in manufacturing where robotic arms with intelligent control perform precise assembly with minimal human input. These dynamic systems learn and adapt over time, improving performance through machine learning algorithms, including reinforcement learning, fuzzy logic, and neural networks, as noted by Hashemi and Dowlatshahi [13].

AI-driven mechatronic systems are transforming supply chain and product development processes. In logistics, they track inventory, predict demand, and optimize deliveries in real time, reducing waste, delays, and costs. For example, predictive maintenance in delivery vehicles helps prevent breakdowns and ensures timely service. In product development, tools like digital twins allow engineers to test and refine designs virtually, speeding up innovation and lowering development costs. These systems also provide valuable insights into product performance and user behavior, guiding future improvements. Figure 4 shows a conceptual flow diagram illustrating how AI-driven mechatronic systems facilitate business process transformation, from real-time data acquisition to operational optimization and product development innovation.



Fig. 4. Business process transformation enabled by AI-Driven mechatronics

B. Digitalization and operational agility

Digitalization is a key enabler of operational agility, and AI-driven mechatronics plays a central role in this transformation. By embedding intelligence into physical systems, organizations can create cyber-physical environments where data flows seamlessly between machines, systems, and decision-makers. This connectivity enables real-time monitoring, diagnostics, and control, which are essential for agile operations.

Operational agility is a key advantage in fast-changing industries like automotive, where technology and customer demands evolve rapidly. AI-powered mechatronic systems enhance this agility by enabling real-time decisions and adaptive control. For example, smart robots in manufacturing can adjust their actions based on sensor data to maintain quality despite shifting conditions. These systems also support mass customization, allowing quick transitions between product variants with minimal delays, meeting individual customer preferences efficiently and at scale.

Digitalization also enhances collaboration across organizational boundaries. Cloud-based platforms and Internet of Things (IoT) technologies enable real-time data sharing between suppliers, manufacturers, and customers. This transparency improves coordination, reduces errors, and fosters innovation. For example, data from AI-driven mechatronic systems in vehicles can be shared with service providers to offer proactive maintenance, enhancing the customer experience and building brand loyalty [14].

C. Case examples and illustrative scenarios

There are many real-world examples that illustrate how AI-driven mechatronics can transform business processes. One notable case is Tesla, which has integrated AI and mechatronics not only into its vehicles but also into its manufacturing and logistics operations. Tesla's Gigafactories use AI-powered robots for tasks ranging from battery assembly to quality inspection. These systems continuously learn from operational data, improving efficiency and reducing defects over time.

Another example is BMW's use of digital twins in its production facilities. By creating virtual models of its manufacturing processes, BMW can simulate changes, identify bottlenecks, and optimize workflows before implementing them on the shop floor. This approach improves flexibility and lowers the risks associated with changes in processes [15].

DHL has integrated AI-driven robots in its warehouses for sorting and packaging. Utilizing computer vision and machine learning, these robots identify items, optimize packing, and navigate efficiently. This automation results in faster processing, lower labor costs, and enhanced accuracy.

D. Challenges and considerations

Despite their advantages, implementing AI-driven mechatronic systems presents several challenges. One key issue is their complexity, as successful integration requires expertise across engineering, data science, and software development. Ensuring reliable performance and seamless communication between components can be technically demanding. Data security and privacy are also critical, with organizations needing strong cybersecurity measures and compliance with regulations like the GDPR. High implementation costs, especially for small and medium-sized enterprises (SMEs), can be another barrier. However, collaborative models and shared platforms are emerging as cost-effective solutions.

Despite these hurdles, AI-driven mechatronics are transforming business operations by enabling automation, real-time decision-making, and digital innovation. Companies that embrace these technologies are better positioned to enhance efficiency, agility, and long-term competitiveness in the digital era.

V. Managerial implications and strategic considerations

As organizations increasingly adopt AI-driven mechatronic systems and embrace innovation as a strategic capability, the role of leadership and governance becomes paramount. The transformation discussed in previous chapters, spanning intelligent systems, digitalization, and business process redesign, cannot succeed without a robust managerial framework that supports innovation, manages change effectively, and cultivates organizational readiness.

A. Innovation governance and leadership

Innovation governance refers to the systems and policies that guide innovation within an organization, ensuring alignment with strategic goals, proper resource allocation, and performance monitoring. In the context of AI-driven mechatronics, governance must also address ethical, technical, and operational challenges. Effective governance starts with a clear innovation vision, supported by actionable plans, defined priorities, measurable outcomes, and clear accountability. As Heilemann and Faix argue, innovation leadership is not about micromanaging creativity but about creating the conditions in which innovation can flourish, conditions that include psychological safety, cross-functional collaboration, and tolerance for failure [16].

Leadership style greatly impacts innovation outcomes. Transformational leadership, which emphasizes vision and empowerment, encourages an innovative culture. Leaders should model openness to new ideas while also challenging established norms. Balancing exploration of novel ideas with optimization of existing capabilities is crucial for maintaining long-term innovation.

B. Change management and organizational readiness

Innovation-led transformation is inherently disruptive. It challenges existing norms, processes, and power structures, often triggering resistance. Effective change management is therefore essential to ensure that innovation initiatives are not only implemented but also embraced by the organization. Figure 5 outlines the core components of a managerial framework necessary for successful innovation-led transformation, highlighting the interdependencies between governance, leadership, change readiness, and organizational culture.

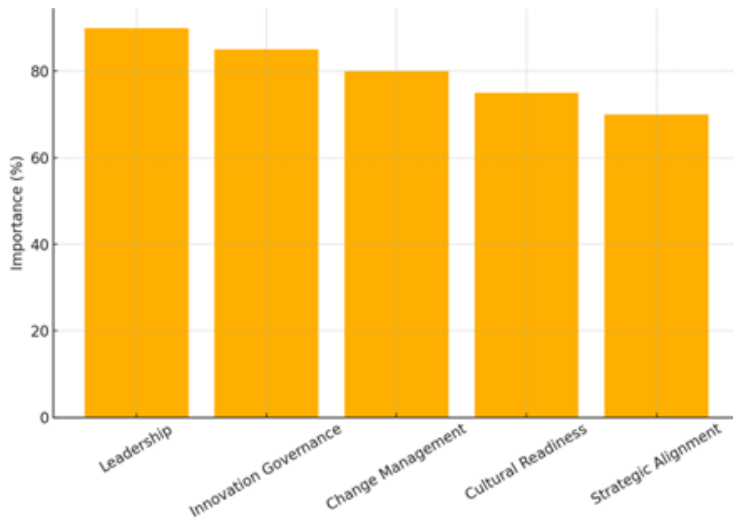


Fig. 5. Managerial pillars of innovation-driven transformation

Figure 5 offers a visual representation of the core components essential for managing innovation-led transformation. The bar chart highlights five key elements, Leadership, Innovation Governance, Change Management, Cultural Readiness, and Strategic Alignment, and ranks them by their relative importance in driving successful transformation.

Together, these components form an interdependent framework that supports innovation-led transformation. Their relative importance, as depicted in Figure 5, underscores the need for a balanced and holistic approach, one that combines visionary leadership, structured governance, proactive change management, cultural adaptability, and strategic coherence.

Change management helps individuals and teams adopt new ways of working. Successful change initiatives share several key elements: a compelling vision, strong leadership, clear communication, stakeholder involvement, and a commitment to continuous learning. These elements are particularly important in the context of AI-driven transformation, where the pace of change can be rapid and the implications far-reaching.

Organizational readiness is critical for successful change. It involves both the willingness and the capacity to implement new initiatives. Many transformations fail not due to poor strategy, but because organizations are unprepared. Leaders must assess readiness early, identifying obstacles and enablers.

To build readiness, companies should invest in training, involve employees in the change process, and establish feedback channels to monitor progress and adapt as needed. Clear and consistent communication is also essential. Leaders must explain the purpose of change, address concerns, and use storytelling to connect the transformation to employees' values, fostering trust and engagement.

VI. Conclusion

The integration of artificial intelligence into mechatronic systems represents a pivotal shift in how organizations conceive, design, and deliver value. This transformation is not confined to technological advancement alone; it extends deeply into the strategic, operational, and managerial fabric of modern enterprises. AI-driven mechatronics fosters innovation and agility, serving as a catalyst in industries' digital transformation.

The evolution of intelligent mechatronic systems combines mechanical engineering, electronics, and software, enabling them to learn, adapt, and make real-time decisions. This shift transforms product development, service delivery, and organizational operations. These systems are now active participants in value creation, responding dynamically to changing environments and user needs.

Innovation is now a strategic necessity. Organizations that embed innovation into their core capabilities, rather than treating it as a side activity, are better equipped to navigate disruption and seize new opportunities. Achieving this requires a clear strategy, strong governance, and a culture that supports experimentation, adaptability, and collaboration.

Digitalization, powered by AI and intelligent systems, has redefined operational excellence. Traditional linear processes are being replaced by agile, data-driven workflows that enable faster decisions, predictive analytics, and greater efficiency. This shift also supports new business models and personalized customer experiences.

Leadership plays a critical role in this transformation. Beyond investing in technology, leaders must foster a culture of innovation, communicate a clear vision, and guide teams through change. Effective change management becomes essential to help organizations and employees adapt.

Ultimately, the success of AI-driven mechatronic systems depends on aligning technology, strategy, and people. Organizations that approach innovation holistically, integrating intelligence across all levels, will be best positioned to lead in the era of smart, adaptive operations.

A. Limitations of the study

While this study provides a comprehensive analysis of strategic innovation management in the context of intelligent mechatronic systems, its scope is deliberately confined to the automotive industry. This sector was selected due to its advanced integration of mechatronic technologies and its pivotal role in driving industrial innovation. However, this industry-specific focus may limit the generalizability of the findings to other sectors, such as aerospace, healthcare, or consumer electronics, where the dynamics of innovation and business process

transformation may differ significantly. Future research could expand the scope to include cross-industry comparisons, thereby offering a broader understanding of how strategic innovation management frameworks apply across diverse technological and organizational contexts.

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THE GREAT FILTER: AN ANALYSIS OF AI STARTUP FORMATION AND INVESTMENT DYNAMICS IN ROMANIA (2020-2025)

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Abstract

This paper examines the profound impact of recent global advancements in Artificial Intelligence on Romania's startup ecosystem between 2020 and 2025. Using a mixed-methods approach, this research identifies a rapid, two-phase evolution: an initial, hype-driven wave of generic "AI Wrappers," followed by a market correction and a "flight to quality" towards defensible, high-ROI "AI Agents." This transition is significantly accelerated by the professionalization of the local investor class, whose strategies have been reshaped by recent market volatility and higher return expectations. The findings indicate that while approximately 60% of AI startups founded during this period fit a generic model, venture capital is increasingly concentrating in the 40% of firms focused on differentiated solutions. The paper concludes that Romania's established strengths in B2B software, combined with this newly discerning investment climate, position its ecosystem to successfully navigate this "Great Filter" and thrive in the next, more mature phase of the AI revolution.

Keywords

Artificial Intelligence, Startup Ecosystem, Venture Capital, Angel Investment, Romania, Generative AI, Platform Shift

I. Introduction

A. Background

The commercial release of advanced Generative Artificial Intelligence (Gen AI) models in late 2022 catalyzed a global technological and economic shift, democratizing access to powerful Artificial Intelligence (AI) and sparking a wave of entrepreneurial activity (Stanford University HAI, 2024). While the impact on major technology hubs has been extensively documented, the effects on emerging startup ecosystems, especially in countries in Eastern Europe, remain less understood.

This paper argues that the Romanian AI startup ecosystem underwent a rapid two-phase evolution: an initial, hype-driven wave of generic "AI Wrappers," riding the post-COVID digital emergence, followed by a market correction and a "flight to quality" towards defensible "AI Agents," a transition powerfully accelerated by a newly professionalized and risk-averse local investor class leveraging the nation's core strengths in B2B software.

B. Research Problem

This study focuses on the Romanian technology ecosystem to analyze how this global AI paradigm shift has manifested at a local level. There is a significant gap in academic literature examining the interplay between a global technology hype cycle and the specific behaviors of the local investor class in an emerging market.

C. Research Questions

How did the proliferation of AI technologies alter startup formation and investment patterns in Romania between 2020 and 2025?

What distinct phases of adoption and maturation can be identified, and what were their primary drivers?

How has the strategic behavior of local investors shaped the trajectory and viability of new AI ventures?

II. Literature Review

A. Global Trends in AI Investment

The period following 2022 is marked by an unprecedented surge in venture capital (VC) investment in AI. The Stanford University HAI "AI Index Report" (2024) shows that while overall VC funding contracted, Generative AI alone attracted \$25.2 billion in 2023. This reflects what economists Agrawal, Gans, and Goldfarb (2018) describe

as a drop in the cost of prediction, spurring innovation in complementary areas. However, this investment euphoria has been met with scrutiny regarding profitability, with recent reports suggesting that a vast majority of corporate Generative AI pilots are failing to demonstrate the ROI needed to secure funding from fiscally-minded CFOs (Fortune, 2025).

B. Startup Ecosystems in Emerging Markets

A startup ecosystem comprises a complex network of actors that interact to foster new venture creation (Isenberg, 2010). In the context of Central and Eastern Europe (CEE), these ecosystems have been catalyzed by "anchor firms"—highly successful local startups creating significant talent and capital spillover effects (Acs et al., 2017). The Global Startup Ecosystem Report (Startup Genome, 2025) provides a framework for analyzing these hubs, whose ability to capitalize on new technology waves depends on their pre-existing industrial structure and human capital.

C. The "Platform Shift" and Defensibility

The rise of foundational AI models represents a classic "platform shift" (Parker et al., 2016). While enabling disruptive innovation (Christensen, 1997), these platforms create a strategic paradox where they tend to capture the majority of the value (Thompson, 2015). This has led to a critical discourse on competitive moats for AI companies. Influential voices in venture capital argue that defensibility must now come from proprietary data and deep workflow integration, as the core model is a commodity (a16z, 2023).

D. The Romanian Tech Ecosystem Pre-AI

Prior to the AI boom, Romania's tech ecosystem had established a strong reputation in B2B software, anchored by the global success of the Robotic Process Automation (RPA) firm UiPath (TechCrunch, 2021). This, along with cybersecurity giant Bitdefender, fostered a deep talent pool and a culture focused on enterprise-grade solutions, a fact reflected in reports from the European Commission's Digital Economy and Society Index (DESI). Furthermore, the success of the likes of UiPath and Bitdefender showed that the path to growth is going outside of Romania in search of bigger and more mature markets.

E. The "Platform Shift" and Defensibility

The final piece of the contextual puzzle is the nature of the local capital itself. The CEE investment landscape is undergoing a significant professionalization. Research

from Roca X (2025a) indicates that local VCs are moving away from generalist strategies to develop specific theses, with "B2B AI" and "Deep Tech" emerging as key focus areas. This specialization is accompanied by more rigorous due diligence processes.

Simultaneously, the profile of the angel investor is changing. A significant portion of local angel capital was impacted by the 2023-2024 "crypto winter," creating a deep-seated skepticism towards hype-driven technology cycles (Roca X, 2025b). This "crypto hangover" has made investors more focused on fundamentals. Furthermore, a new wave of High-Net-Worth Individuals (HNWIs) from traditional industries is entering the asset class. As noted by The Recursive (2025), this capital is highly pragmatic, ROI-focused, and often directed towards B2B solutions that these investors understand from their own industries. This confluence of factors creates a more discerning and sophisticated early-stage investment environment than in previous technology cycles.

III. Methodology

A. Research Design

This study employs a mixed-methods research design, structured as a longitudinal study of the Romanian ecosystem from January 1, 2020, to August 28, 2025. This approach allows for the triangulation of quantitative findings on market trends with qualitative insights into the strategic behavior of founders and investors. This approach was chosen because one of the main characteristics of emerging markets and ecosystems is the lack of a clear, unbiased overview of all economic actors. There is no "go-to reference" for finding new start-ups and firms in the tech space; at the same time even for established and very public new start-ups, the habit of pivoting with the time and the emerging tech makes evaluating their core product/services challenging.

B. Data Collection

A composite dataset was constructed by aggregating information from multiple sources:

- **Primary Database:** Dealroom.co was used to identify newly founded AI-tagged startups and track funding events.
- **Qualitative Investor Data:** A key component of this study involved analyzing reports on investor sentiment and strategy from local market actors like Roca X and regional tech publications such as The Recursive. These reports provided crucial context on the motivations behind the observed funding patterns.

- Cross-Validation: Data was cross-referenced with industry reports from How to Web, VC portfolios, and high-level statistics from Romania's National Trade Register Office (ONRC).

C. Data Analysis

Quantitative Analysis:

A time-series analysis was performed on startup formation and funding data, segmented by year and investment stage (pre-seed/seed vs. Series A+).

Qualitative Analysis:

A thematic analysis was conducted on the business models of an N=965 sample of AI-tagged startups. Each company's value proposition, as described on its website and in its professional profiles, was coded into one of two categories. The criteria were as follows:

Generic AI: Startups were coded as "Generic" if their product was a horizontal application of a foundational model API with no evidence of significant proprietary data or deep workflow integration (the "AI wrappers"). Keywords for this category included "content generator," "AI assistant," and "chatbot builder."

Vertical AI: Startups were coded as "Vertical" if their product addressed a specific industry problem, explicitly mentioned the use of proprietary datasets for training or fine-tuning, and described integration into core business workflows. To ensure consistency, a subset of the data was independently coded by a second reviewer, achieving a high degree of inter-coder reliability.

D. Limitations of the Study

This study has several limitations. As mentioned earlier, data on the local market, and even more so on private market transactions, is not public or easily accessible, which forced an estimate. At the same time, the qualitative classification is based on public-facing materials and internal reports provided by Roca X and other players in the VC space. Most notably, while the above-mentioned reports from Roca X and the like provide invaluable insight, they represent a sample of investor sentiment, not a complete census of the market. To conclude, the study is, by necessity, more focused on trends and market sentiment as a proxy for the state of the local tech entrepreneurial ecosystem.

IV. Findings: The Quantitative Landscape of Romanian AI: (2020-2025)

A. An Accelerated Growth Trajectory

The data reveals a significant and accelerating trend in the formation of AI-focused startups in Romania, with the number of new ventures surging dramatically in 2023

and 2024, corresponding directly with the popularization of Generative AI. As a percentage of all new tech startups, AI-focused companies grew from an estimated 6.8% in 2020 to over 23.8% in H1 2025.

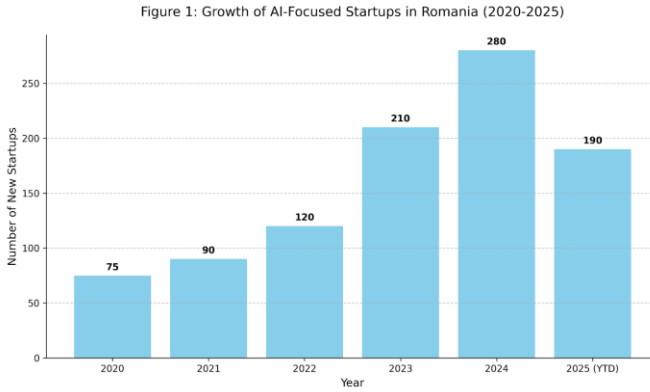


Fig. 1. Growth of AI-focused Startups in Romania (2020-2025), est.

B. A Bifurcated and Professionalizing Funding Environment

Venture capital patterns reveal a distinct bifurcation. As shown in Figure 2, the volume of early-stage (pre-seed/seed) deals surged in 2023-2024 before correcting in 2025. This correction can be attributed to market saturation and a more discerning approach from early-stage investors. The concentration of significant, later-stage capital (Series A+) in a smaller number of "Vertical AI" companies has shown more resilient growth. This reflects the strategy of local VCs, who are reportedly reserving more capital for follow-on funding for their proven portfolio winners (Roca X, 2025a), making the first check for new ventures more competitive.

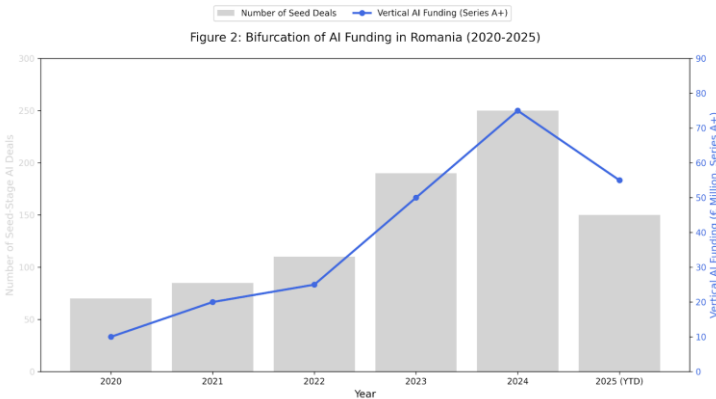


Fig. 2. Bifurcation of AI Funding in Romania (2020-2025), est.

C. The Emergence of the "Wrapper" Cohort

The qualitative analysis reveals that approximately 60% of all AI startups founded during the period fall into the "Generic AI" category, with the vast majority emerging after March 2023.

The 40% classified as "Vertical AI" are more evenly distributed and, while smaller in number, have attracted a significantly larger share of the total venture capital invested, mostly due to the perceived "defensibility" factor of their individual databases and the focus on clearly defined business problems that they are trying to solve.

V. Analysis and Discussion: Navigating the "Great Filter"

The findings paint a picture of an ecosystem undergoing a "Great Filter"—a rapid market maturation process that sorts a large volume of AI experiments into a smaller cohort of viable businesses. This filter is not merely a passive market force; it is actively enforced by a newly professionalized and skeptical investor class.

A. Phase 1: The Hype Cycle (2023-2024) – A Technology in Search of a Problem

The explosion of "Generic AI" startups was a classic reaction to a platform shift, enabled by easy access to LLM APIs. This phase was characterized by a focus on technological possibility over business viability, leading to a crowded market of low-defensibility "AI wrappers." This mirrored the global trend of widespread AI experimentation with questionable ROI.

An alternative explanation here would be to view AI as a technology seeking a problem to solve (a "real use case"), rather than taking a painful, clearly defined problem and developing a solution for it.

B. Phase 2: The Flight to Quality (2025) – The Investor-Driven Correction

The shift to Phase 2 is a systemic correction driven by a newly discerning investor class. The Roca X (2025) reports provide compelling evidence for this transformation. A key psychological driver is the "crypto hangover"; having been burned by the previous hype cycle, investors are now deeply wary of the buzz surrounding Generative AI, demanding strong fundamentals from the outset. This scepticism is reinforced by financial logic; with median return expectations of 14x, investors are mathematically compelled to ignore low-moat "wrapper" businesses in favor of startups with the potential for massive, defensible scale. Furthermore, the influx of pragmatic capital from traditional industry High-Net-Worth Individuals (The Recursive, 2025) and the strategic shift of VCs towards B2B AI and

Deep Tech concentrates capital on precisely the sort of defensible, high-ROI companies that are best positioned to survive. This confluence of factors—investor psychology, financial modelling, and strategic specialization—is what gives the "Great Filter" value, rapidly separating fleeting AI experiments from enduring businesses.

C. Strategic Imperatives for Defensibility: The "MedicAI" Archetype

In this sharpened investment climate, survival depends on defensibility. As argued in the literature (a16z, 2023), moats must be built beyond the commoditized AI model. Our analysis of the "Vertical AI" cohort reveals two primary sources of defensibility:

Proprietary Data - using the archetype of a startup like "MedicAI" (<https://www.medicalai.io/>), its value is derived from its unique, curated, and compliant dataset, which allows it to achieve superior performance on a specific, high-stakes task.

Deep Workflow Integration - the second moat is embedding the AI solution so deeply into a customer's critical business processes that it becomes indispensable, creating high switching costs.

D. Romania's Competitive Advantage

This flight to quality and the strategic imperatives of data and workflow integration play directly to the Romanian tech ecosystem's established strengths. The legacy of UiPath has created a generation of entrepreneurs and engineers who are experts in analyzing and automating complex enterprise workflows. As the global AI market matures beyond simple wrappers, it is moving towards a problem-space where the Romanian ecosystem, now supported by an increasingly sophisticated investor base, has a natural competitive advantage. The challenge is no longer building a clever AI tool, but building a robust, integrated AI automation engine that can deliver the 14x returns investors now demand.

VI. Conclusion

A. Summary of Findings

This paper has analyzed the evolution of the Romanian AI startup ecosystem, identifying a two-phase model: a hype-driven wave of "AI Wrappers," followed by a market correction and a "flight to quality" towards vertical "AI Agents." This "Great Filter" is actively enforced by a newly professionalized investor class, shaped by recent market lessons and higher return expectations.

B. Contribution to Knowledge

This study contributes to the literature by providing a detailed analysis of how a CEE ecosystem has navigated the Generative AI platform shift, uniquely linking global technology trends to local investor psychology and behavior. The model of an investor-accelerated "Great Filter" offers a useful framework for understanding the maturation of other emerging tech hubs.

C. Implications for Stakeholders

For Entrepreneurs, sustainable value lies in solving specific, high-value vertical problems where proprietary data and deep workflow integration can create a lasting moat that satisfies the rigorous ROI demands of the current investment climate.

For Investors, the era of passively betting on hype cycles is closed. Successful early-stage investing in AI now requires deep sector expertise, rigorous due diligence, and a focus on the fundamental drivers of defensibility and profitability.

For Policymakers, policy should focus on supporting the development of these defensible businesses, for instance, by facilitating access to public data for training specialized models and supporting talent development in enterprise software.

D. Future Research

Future research could include a longitudinal study tracking the survival rates of the "wrapper" cohort or a comparative study analyzing how investor sentiment in other CEE countries has shaped their respective AI ecosystems.

Furthermore, a future study could look into how (new) fiscal policy affects funding in the start-up space as well as looking into the steady but almost guaranteed results of investing in Romanian government bonds vs taking a risk on investing venture capital in emerging tech.

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STUDIES IN PRODUCTION ENGINEERING AT THE FACULTY OF TECHNICAL SCIENCES: AN ANALYSIS OF THE ENROLLMENT AND STUDY SUCCESS

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Abstract

Studies at the Department of Production Engineering, Faculty of Technical Sciences, University of Novi Sad are realized at all three national academic qualification levels, namely: Undergraduate academic studies in Production Engineering, Master academic studies in Production Engineering, and Doctoral academic studies in Mechanical Engineering, as well as at one level of professional studies, i.e., Master professional (applied) studies in Production Engineering. This paper presents the analysis of enrollment and study in the study programs of academic and professional studies of production engineering in the period from the academic year 2014/15 until the 2024/25 academic year.

Keywords

Mechanical engineering; Faculty of technical sciences; Department of production engineering; Study programs; Enrollment analysis; Study success analysis

The activity of higher education in the Republic of Serbia is realized through academic and applied (professional) studies by conducting accredited study programs, according to the law on higher education [1]. In academic studies, programs are conducted that train students in the development and application of scientific, artistic, and professional achievements. In applied (professional) studies, study programs are conducted that equip students with the knowledge and skills necessary for the application and development of professional expertise required for inclusion in the work process.

The Law on higher education in the Republic of Serbia divides studies into three levels. Completing each level leads to a specific degree of professional qualification, as shown in Figure 1.

First-level (cycle) studies include Undergraduate Academic Studies (Bachelor's), Bachelor's Applied Studies, and Specialist Applied Studies. Graduates of these programs achieve a professional qualification of 6, 6.1, or 6.2. Second-level (cycle) studies include Master's Academic Studies, Master Applied Studies, and Specialist Academic Studies. These lead to a 7th degree of professional qualification, specifically 7.1 and 7.2. Some academic programs combine undergraduate and master's studies and are called Integrated Academic Studies, which lead to the 7.1 degree. Third-level (cycle) studies include Doctoral Academic Studies, which lead to the 8th level of professional qualification. At the Faculty of Technical Sciences, all types of studies are offered except Integrated Academic Studies (IAS). Academic studies here include Undergraduate Academic Studies (UAS), lasting 4 academic years or 8 semesters, totalling 240 ECTS. Master Academic Studies (MAS) last 1 school year or 2 semesters, totaling 60 ECTS. Doctoral Academic Studies (DAS) last 3 years or 6 semesters and are worth 180 ECTS.

After completing their studies, students receive professional, academic, and scientific titles, as defined by the rulebook [2]. For mechanical engineering, these titles are listed in Table 1. The table highlights the types of studies and the corresponding titles awarded at the Department of Production Engineering (DPE) of the Faculty of Technical Sciences in Novi Sad (FTS).

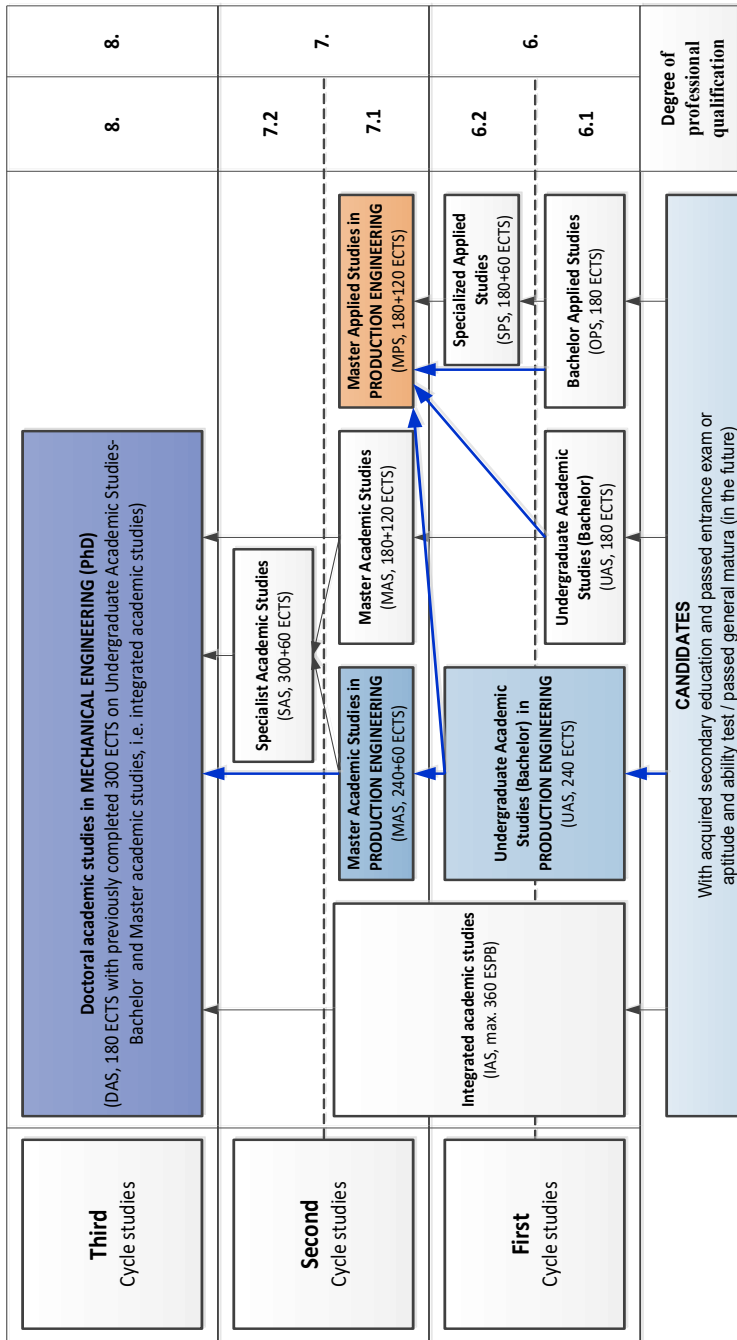


Fig. 1. Levels of education and the corresponding acquired level of professional qualification in the Republic of Serbia with an emphasis on study programs at the Department of Production Engineering of the FTS in Novi Sad

Table 1. List of professional, academic and scientific titles in the field of production engineering at FTS

Level of studies	Types of studies	Professional, academic and scientific title
<i>Academic Studies</i>	(UAS) Undergraduate Academic Studies (Bachelor) in Production Engineering (240 ECTS)	Bachelor's in Mechanical Engineering
	(MAS) Master Academic Studies in Production Engineering (300 ECTS)	Master's in Mechanical Engineering
	(DAS) Doctoral Academic Studies in Mechanical Engineering (480 ECTS)	Doctor of Science in Mechanical Engineering
<i>Applied (professional) Studies</i>	(MPS) Master Applied (Professional) Studies in Production Engineering (300 ECTS)	Professional Master's in Mechanical Engineering

Studies at the Department of Production Engineering, Faculty of Technical Sciences, University of Novi Sad are realized at all three national academic qualification levels, namely: Undergraduate academic studies in Production Engineering, Master academic studies in Production Engineering, and Doctoral academic studies in Mechanical Engineering, as well as at one level of professional studies, i.e., Master professional (applied) studies in Production Engineering [3].

This manuscript presents the analysis of enrollment and study in the study programs of academic and professional studies of production engineering in the period from the academic year 2014/15 until the 2024/25 academic year. Based on this analysis, a policy for enrolling in studies and raising the quality of the implementation of the teaching process at the Department of Production Engineering can be created in the future. The analysis was carried out based on data obtained from the student service on the number of students enrolled at the faculty, which are used to analyse enrollment and study results, as well as to define the workload of the teaching staff.

The basic hypothesis of the research: The number of students enrolled in the first year of Undergraduate Academic Studies (Bachelor) in Production engineering, as well as the passing percentage of students in higher years is gradually increasing, while the number of students enrolled in Master Academic Studies in Production

engineering and Master Applied (Professional) Studies in Production engineering is variable in the last ten school years.

II. Education in the Field of Production Engineering at FTS

The Faculty of Technical Sciences of the University of Novi Sad was founded in 1960 as the Faculty of Mechanical Engineering. The strong development of the economy and the needs of society contributed to the launch of new professions of electrical engineering and civil engineering, so in 1974, the Faculty of Mechanical Engineering grew into the Faculty of Technical Sciences within the University of Novi Sad [4].

The Faculty of Technical Sciences was accredited for the first time under the Bologna Declaration in 2007 for conducting scientific activities, and then re-accredited in 2010, 2013, and 2020. Currently, more than 85 study programs at all levels are accredited at the faculty, covering the technical-technological, natural-mathematical, artistic, and medical fields through interdisciplinary studies. More than 2,500 students enrol at the faculty annually, and currently, around 17,500 students are studying at all levels of study. The faculty consists of 13 departments: Production Engineering; Mechanization and Design Engineering; Energy and Process Engineering; Technical Mechanics; Power, Electronic and Telecommunication Engineering; Computing and Control Engineering; Civil Engineering and Geodesy; Traffic Engineering; Architecture and Urban Planning; Industrial Engineering and Management; Graphic Engineering and Design; Environmental Engineering and Occupational Safety Engineering; and Fundamental disciplines in Engineering. [4].

The Department of Production Engineering, formerly the Institute of Production Engineering, is the institution with the longest tradition at the Faculty of Technical Sciences, having been established in 1960. Through its study programs, the department has produced more than 2,000 engineers, graduate engineers, master engineers, masters, and doctors of science in the field of production engineering, who today are employed in numerous economic and educational institutions in Serbia, the former countries of Yugoslavia, but also in numerous countries of the EU and the world. In more than half a century of work and development, notable personnel and significant material potentials have been created, which represent a guarantee of success in educational and scientific research work.

The Department of Production Engineering is organized into five chairs: Chair of Material processing technologies, Chair of Machine tools, Process planning, Flexible manufacturing systems and Design processes, Chair of Materials and Joining Technologies, Chair of Forming Technologies and Surface Engineering, Chair of Metrology, Quality, Fixtures, Cutting Tools, and Environmental-engineering aspects. The Department has 15 laboratories at its disposal: Conventional Machining Methods; Unconventional Machining Methods; Machine

Tools Technological systems and Design automation; Process planning, Technoeconomical Optimization and Virtual Design; Material Testing; Joining Technologies; Casting; Thermal Processing and Surface Engineering; Plastic Deformation Technology; Polymers; Additive and Virtual manufacturing; Metrology, Quality and Reverse Engineering; Technical diagnostics, Tribology, Cutting Tools and Fixtures; Environmental-engineering aspects and Computer Integrated Manufacturing (CIM) [5].

The department currently has 58 employees, of which 29 are teachers (12 full professors, 12 associate professors and 5 assistant professors), 19 associates (1 assistant with a doctorate, 14 master's assistants, 4 teaching associates), 3 researchers (1 research associate and 2 research trainees), 6 laboratory workers, and 1 administrative worker. The department publishes two international scientific journals, *Journal of Production Engineering and Advanced Technologies and Materials*. Since 1976, it has been organizing the International scientific and professional conference MMA - Flexible technologies, and since 2006, the Scientific conference with international participation ETIKUM. The department is a member of the Association of Scientific Research Institutions of Production Engineering of Serbia, within which it has organized several times the International Conference on Production Engineering of Serbia (formerly Yugoslavia).

Education at the Department of Production Engineering of the Faculty of Technical Sciences includes all three levels of academic studies and one level of professional (applied) studies that were last accredited in 2020. (Figure 1):

- ***Undergraduate Academic Studies (Bachelor) in Production Engineering***
(4 years, 8 semesters, 240 ECTS, title: Bachelor in Mechanical Engineering)
Number of students for enrollment: 80 budget students + 20 self-financing students
- ***Master's Academic Studies in Production Engineering***
(1 year, 2 semesters, 60 ECTS, title: Master's in Mechanical Engineering)
Number of students for enrollment: 25 budget students + 45 self-financing students
- ***Doctoral Academic Studies in Mechanical Engineering***
(3 years, 6 semesters, 180 ECTS, title: Doctor of Science in Mechanical Engineering)
Number of students for enrollment: 5 budget students + 25 self-financing students

- ***Master Applied (Professional) Studies in Production Engineering***
(2 years, 4 semesters, 120 ECTS, title: Master's degree in mechanical engineering)
Number of students for enrollment: 8 budget students + 24 self-financing students

Within the framework of academic studies, students can choose one of four modules, i.e., study groups: Computer Aided Technologies (abbr. CAT), Modern Materials Forming Technologies (abbr. MMFT), Modern Plastics Forming Technologies (abbr. MPFT), and Software for Mechanical Engineering (abbr. SM).

Some of the characteristics of the Department of Production Engineering at the Faculty of Technical Sciences in Novi Sad are:

- 30 doctors of science, 18 associates and 3 researchers participate in the teaching process (with over 500 papers on the SCI list)
- All teachers were participants in a large number of domestic and international scientific, research and professional projects, most of which were realized in cooperation with the economy,
- Availability of modern professional equipment (machines and devices), as well as appropriate information resources (hardware and software), which are distributed in 15 laboratories
- Great cooperation with business entities, signed contracts of scientific and technical cooperation and contracts on the implementation of professional practice,
- Significant representation of career education from various scientific and professional fields in the form of lectures, courses, seminars, trainings, etc.,
- Having a library with a huge number of literary sources, etc.

In this chapter, the Faculty of Technical Sciences and, within it, the Department of Production Engineering are briefly presented, in order to clearly see the importance and role of this faculty and department in the education of mechanical engineers in AP Vojvodina and the Republic of Serbia. Based on the great interest of business entities in the territory of AP Vojvodina and the surrounding area for mechanical engineers (Continental, Nidec, BMTS Technology, ZF Serbia, Grundfos, Bosch, Unimet, FKL, Termometal, LPO, ATB Sever, Siemens, Cooper Standard, Telsonic, Le Belier, IGB Automotive, Tarkett, Grindex, Hutchinson, Mecafor, etc.), as well as the inability of the faculty to educate a sufficient number of them within the quota set for enrollment in studies in the field of mechanical engineering and of the number of students who complete their studies, the idea came to carry out an appropriate analysis of enrollment and study success at the Department of Production Engineering.

III. Analysis of Enrollment and Studies in Study Programs of the Department of Production Engineering

Table 2 shows the analysis of enrollment in the last 11 school years (from 2014/15 to 2024/25) in the study programs UAS (Undergraduate Academic Studies in Production engineering), MAS (Master Academic Studies in Production engineering) and MPS (Master Applied (Professional) Studies in Production engineering) within the Faculty of Technical Sciences in Novi Sad. Figure 2 shows a graphic representation of these data.

Table 2. Analysis of enrollment in study programs in production engineering at FTS¹

School years	UAS Production Engineering	MAS Production engineering				MPS Production Engineering
		Study group CAT	Study group MMFT	Study group MPFT	Total	
2024/25	100	21	4	3	28	17
2023/24	100	23	22	-	25	8
2022/23	100	16	7	3	26	17
2021/22	94	5	8	4	17	20
2020/21	100	13	10	1	24	17
2019/20	96	11	12	2	25	-
2018/19	92	12	16	4	32	-
2017/18	87	17	8	3	28	-
2016/17	84	16	5	4	25	-
2015/16	82	7	8	4	19	-
2014/15	77	12	11	2	25	-
Total	1012	153	111	30	274	79

¹ Note: The data in tables 2 and 3 are taken from the number of students for the teaching load at FTS. These data do not show whether the mentioned students studied regularly, i.e. whether they renewed their years of study.

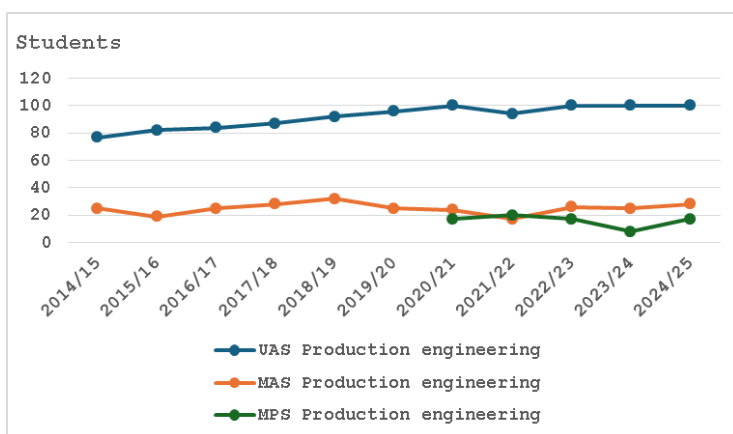


Fig. 2. The number of students enrolled in the study programs of the Department of Production Engineering

Based on the data in Table 2, the following conclusions were drawn. Considering the great need of business entities in the territory of the Republic of Serbia and the environment for mechanical engineers, interest in this type of study has grown significantly in the last period, as indicated by the number of students enrolled in the UAS in production engineering, especially in the last couple of years, when the maximum number of students was enrolled. On the other hand, due to the large lack of mechanical engineers on the labor market, students begin to get involved in the work process already in the third or fourth year of study (through professional practices, as an intern or by concluding an employment relationship), i.e. after obtaining a diploma in mechanical engineering, which also affects the number of students enrolled at MAS in production engineering.

Table 3 shows the analysis of study success for the last 11 school years, through the percentage of passing from 1st to 2nd year, from 2nd to 3rd year, from 3rd to 4th year of study, then passing from 1st to 4th year, from 4th year of UAS to 1st year of MAS and from 1st year of UAS to 1st year of MAS.. A graphical representation of the data from Table 3 is given in Figures 3, 4 and 5.

Table 3. Analysis of the success of studying on the UAS and MAS production engineering study programs at FTS

School years	UAS				MAS	Pass rate/enrollment rate in multiple years of study (%)					
	1st year	2nd year	3rd year	4th year		1st to 2nd year	2nd to 3rd year	3rd to 4th year	1st to 4th year	4th year of UAS to 1st year of MAS	1st year of UAS to 1st year of MAS

						UA S	S	S	S		
2024/25	100	53	51	50	28	53,0 0	86,4 4	86,2 1	53,1 9	62,22	28,00
2023/24	100	59	58	45	25	59,0 0	89,2 3	75,0 0	45,0 0	39,68	26,04
2022/23	100	65	60	63	26	69,1 5	86,9 6	103,28	65,6 3	53,06	28,26
2021/22	94	69	61	49	17	69,0 0	81,3 3	87,5 0	53,2 6	30,91	19,54
2020/21	100	75	56	55	24	78,1 3	91,8 0	94,8 3	63,2 2	51,06	28,57
2019/20	96	61	58	47	25	66,3 0	100, 0	95,9 2	55,9 5	53,19	30,49
2018/19	92	58	49	47	32	66,6 7	74,2 4	104,44	57,3 2	82,05	41,56
2017/18	87	66	45	39	28	78,5 7	71,4 3	92,8 6	50,6 5	59,57	-
2016/17	84	63	42	47	25	76,8 3	93,3 3	92,1 6	-	56,82	-
2015/16	82	45	51	44	19	58,4 4	92,7 3	112,82	-	79,17	-
2014/15	77	55	39	24	25	-	-	-	-		
Avrg. value	92,0	60,8	51,8	46,4	24,9	67,5	86,8	94,5	55,5	56,8	28,9

Based on the data from Table 3, it can be concluded that the worst passing rate of students from the 1st to the 2nd year is UAS (67.6%), while in the following years, this percentage increases, from the 2nd to the 3rd year (86.8%), and from the 3rd to the 4th year (94.5%). The analysis shows that slightly more than half of the enrolled students (55.5%) pass from the 1st to the 4th year of UAS. The percentage of students who from the 4th year of UAS enroll in MAS studies is only (56.8)%, for which the

justification should be sought in the fact that the economy also seeks and employs mechanical engineers without a master's degree. Likewise, the analysis shows that less than 1/3 of students (28.9%) who start UAS studies enroll in MAS studies.

The lowest passing rate is in the 1st to 2nd year of UAS studies, which may be linked to the transition from high school to higher education, i.e., a more difficult adaptation to study requirements due to changes in the way of working at the university compared to high school. In the higher years, the percentage of passing in the higher year of study is much higher, which can be justified by the fact that less prepared and poorer students dropped out of their studies, while those who remained had already adapted to the way of studying, as well as by the fact that students have a greater motivation as the end of their studies and the possibility of employment approaches.

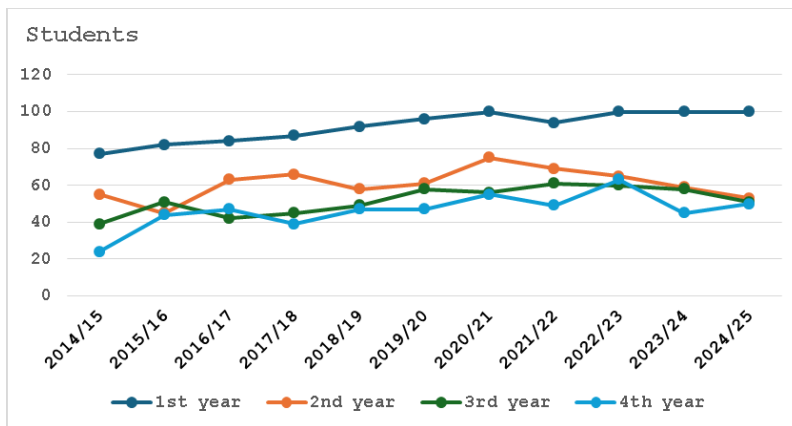


Fig. 3. Number of students enrolled in 1st to 4th year of Undergraduate Academic Studies (Bachelor) in Production engineering in the last 11 school years

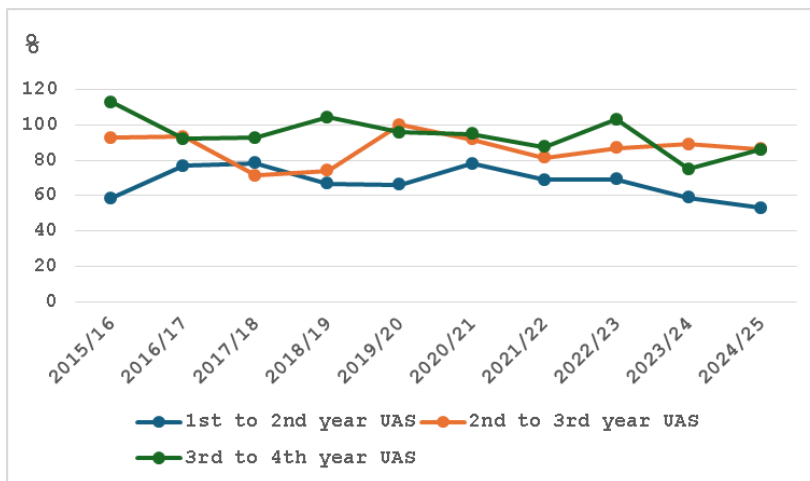


Fig. 4. Percentage of passing students from the lower to the upper year in the study program UAS production engineering

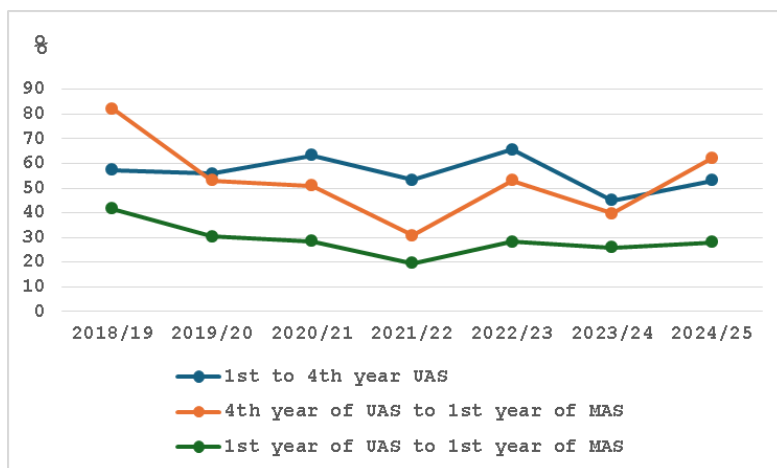


Fig. 5. Study success in the study programs UAS and MAS Production Engineering

Table 4 shows the analysis of first and second year enrollment in the observed study program Master Applied (Professional) Studies in Production engineering at the Faculty of Technical Sciences in Novi Sad.

Table 4. Analysis of the enrollment and passing rates of students in the Master Applied (Professional) Studies in Production engineering at the FTS

School years	Number of students enrolled in the 1st year			Number of students enrolled in the 2nd year	Passing of students from 1st to 2nd year in percentage (%)
	Budget students	Self-financing students	Total		
2024/25	8	9	17	5	62,5
2023/24	8	0	8	14	82,4
2022/23	8	9	17	19	95,0
2021/22	8	12	20	15	88,2
2020/21	8	9	17	-	-
Average value	8	8	16	13	82,0

Based on the analysis of the previous table, it can be concluded that there is justification for the realization of the study program of Master Applied (Professional) studies in Production Engineering (MPS), but that the number of enrolled students is still significantly lower than the accredited one. It is also concluded that the success in the MPS studies in Production Engineering (on average about 82% pass rate from 1st to 2nd year, for the period 2021/22-2024/25) is significantly better than the pass rate in the UAS studies in Production Engineering, which can be interpreted by the fact that the enrolled students are more serious, have previously completed UPS (Undergraduate Applied (Professional) Studies) or UAS studies, and a large percentage of them are employed, they understand the studies as an opportunity to improve their knowledge, and their diploma is required for advancement at work or obtaining licenses from the Serbian Chamber of Engineers.

In addition to the above, the block method of teaching in these studies has a significant impact on higher passing rates, where students can take exams immediately after listening to a block of classes in two subjects. An increase in the enrollment of students from outside the AP Vojvodina has been observed, so it is expected that an increasing number of such students will enrol as information about the quality and opportunities of these studies spreads [6].

IV. Conclusion

This paper presents an analysis of enrollment and studies in academic and professional study programs in production engineering for the period from 2014/15 to 2024/25 academic year at the Faculty of Technical Sciences in Novi Sad.

Based on the extensive analysis for the UAS (Undergraduate Academic Studies in Production engineering), MAS (Master Academic Studies in Production engineering) and MPS (Master Applied (Professional) Studies in Production engineering) study programs, a final review can be given:

- The number of students enrolling in the first year of UAS has increased by 20% in the last couple of years,
- The passing rate of students from the 1st to the 2nd year of UAS is the lowest and ranges from 53-78% (average 67.5%), while it increases significantly in higher years, from the 2nd to the 3rd year (average 86.8%), and from the 3rd to the 4th year (average 94.5%).
- The percentage of students who go from the 1st to the 4th year is 45-65% (average 55.5%), the percentage of those who enroll in MAS after graduation is 40-82% (average 56.8%), while the percentage of students who enroll in MAS out of the number enrolled at UAS is about 26-42% (average 28.9%)
- The number of students at MPS is constant and is in the range of 17-20 (exception in 2023/24).

- The passing rate of students from the 1st to the 2nd year of MPS is quite high and ranges from 62-95% (average 82%)

This analysis is very useful for the creation of enrollment policy and the implementation of the teaching process, with numerous aspects such as the number and structure of students for enrollment in study programs (number of budget and self-financing students), planning the number and structure of teaching staff in the future, analysis of bottlenecks and passing of students and enrollment in the following years of study, the possibility of satisfying the number of mechanical engineers according to the needs of the industry, etc.

The above data can be very useful as a basis for creating an enrollment policy at all levels of study and for implementing the teaching process at the Department of Production Engineering of the Faculty of Technical Sciences. The Faculty of Technical Sciences is currently in the process of re-accreditation of study programs, which should be completed during the next year, and students will be accepted from the academic year 2027/28. educated on newly accredited study programs. The Department of Production Engineering initiated the reaccreditation of all the mentioned study programs (UAS, MAS, MPS and DAS) with significant improvements that partially resulted from the subject analysis presented in this paper.

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STRATEGIC MANAGEMENT FOR THE RELAUNCH OF ROMANIA'S ARMAMENTS INDUSTRY IN THE NEW INTERNATIONAL CONTEXT

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Abstract

We live in a volatile world where decisions must be made quickly. Every individual and every idea can influence peace or conflict and therefore, it is good to always be prepared for what comes next. In the current international context where the great powers of this world divide resources, areas of influence, as well as the rights to make peace and war, thinking of a strategic management plan for the relaunch of Romania's armament industry represents a necessity. Romania's longstanding geostrategic position has historically placed it at a disadvantage, a situation that is becoming increasingly visible today as Romania finds itself at war's doorstep, at the intersection of NATO, the EU, and Russia. We are increasingly faced with the necessity of defense and alignment with the NATO/EU strategy for strategic thinking in the armament industries of each member state. Why am I addressing this topic? At this moment, I am directly involved in this process as an employee of C.N. ROMARM S.A-Filiala S. U.P.S Dragomiresti S.A., and I wish to bring a new vision to this field, a strategic management approach that correlates the national framework with the international one, applying patented management methods as well as specialized studies, offering a new vision for this domain. While analyzing a moving target is difficult, envisioning future directions is both challenging and rewarding, in order to gain a competitive advantage in this field. For this reason, I chose to delve deeper into this current and future topic.

Keywords

Strategic management, Strategic planning, Organizational competence analysis

I. Introduction. Presentation of the current situation in Romania

Romania currently has 22 state-owned companies in the defence industry - their combined turnover in 2023 is 1.1 billion euros. The main producer and direct exporter of military products in Romania, the National Company ROMARM S.A. was established in 2000 through the merger of the most important factories of the Romanian Defence Industry. C.N. ROMARM is the main supplier of military equipment, ammunition, and maintenance services in Romania. The National Company ROMARM has a holding structure, with 100% Romanian capital, and is under the authority of the Ministry of Economy, Entrepreneurship, and Tourism. In most of the factories - where, for example, ammunition, explosives, weapons, and projectiles are produced - they have not been modernized for decades, the technology they use is outdated, and a large part of the production is not aligned with NATO standards, of which Romania has been a member for over 20 years. Romania has been lagging behind in the European Union regarding the money it generally allocates to research. In 2023, for the sixth consecutive year, in last place in the EU in the ranking of investments in research and development. Only 0.12% of GDP went to this sector - around 400 million euros. My goal in the study I am about to conduct is to introduce new elements described succinctly hereafter, starting from these rather disappointing data for Romania.

Following, as I mentioned, for an accurate and precise documentation of Romania's strategy in this vital field, we can analyze the statements of Mr. Bogdan Gruia-Ivan, the Minister of Economy: "In the companies owned by the Ministry of Economy that have state capital, we are bringing the latest technology and starting to produce NATO-compatible ammunition, compatible with the Abrams tank purchased by the Romanian army from the USA, and we are also starting to export to other countries." What we are doing concretely is that we have the land, the production halls, we are purchasing intellectual property with them, and the profit obtained from the sale of all that means ammunition will be shared according to the agreement between the American partner and us." Mr. Bogdan Gruia-Ivan, Minister of Economy, again: "We are in advanced negotiations and by the end of the year we will have two production lines for TNT and RDX explosives operational, using technology from Germany. On the other hand, we have an important project to produce powders in Romania at Pirochim Victoria. In just these hours, we have concluded the letters of intent to Rheinmetall to agree on the final form. On the other hand, we are investing 20 million euros at Carfil in Braşov, building from scratch the first armaments factory in Romania in the last 40 years."

It is current news that after two years of receiving limited funds, the state-owned factories in the Defense industry will have an addition of one billion lei to the budget in 2025. The money will go to only a few strategic projects, which, however, are

progressing slowly and will not lead to immediate production for the Romanian Army.

This year, on March 6, the European Union announced a massive armament plan worth 800 billion euros. Now, each member state must increase its defense budgets so that, together, the 27 countries of the community bloc invest 650 billion euros in new ammunition, defense systems, military mobility, and artificial intelligence. However, the European Union wants to add another 150 billion euros for defense strengthening, from loans made on behalf of the member states. But in 2025, the Ministry of Economy received an additional one billion lei (200 million euros) from the budget, beyond current expenses, for the production of ammunition and military equipment. The most important military projects that the Ministry of Economy is betting on are: the construction of a powder factory; the manufacturing, in two subordinate plants, of NATO-caliber ammunition 120-155 mm; the production in Romania of Infantry fighting vehicles and individual weapons for soldiers.

II. Theoretical Framework. Strategic Management for the Relaunch of the Armaments Industry

In this section, we aim to discuss what strategic management means at a theoretical level in order to see and understand how this relatively new science, which has been the subject of multiple scientific papers and is widely talked about lately, works. It is very important to understand that strategic management is the one in which the company's leadership is based on strategies. Practice has shown that an organization cannot carry out activities with high long-term profitability if it does not have a well-founded strategy adapted to its specific conditions.

Primarily, it is essential to define the term strategic planning in the case of organizations. To be more precise, it is necessary to discuss the implementation of a coherent and functional strategy. We believe it is advisable to consider the company's mission, strategic objectives, strategic options, resources, deadlines, synergy, competitive advantage, or distinctive competence.

Vision and Mission Development: Establishing a clear vision helps an organization define what it aspires to become in the future, while the mission outlines its purpose and core values. This foundational step guides all strategic decisions. [1]

Environmental Analysis: Organizations conduct SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) to understand their internal capabilities and external market conditions. This helps identify areas for growth and potential challenges.

Strategy Formulation: Based on the insights gained from the analysis, organizations develop strategies that leverage their strengths, mitigate weaknesses,

capitalize on opportunities, and defend against threats [2]. This could involve market expansion, product development, or diversification.

Strategy Implementation: This involves translating strategic plans into actionable steps. It includes resource allocation (financial, human, technological), establishing timelines, and ensuring that all team members understand their roles in achieving strategic goals.

Performance Monitoring and Evaluation: Organizations set key performance indicators (KPIs) to measure progress. Regular reviews and assessments ensure that the strategy remains aligned with the organization's goals and allows for adjustments as necessary [3].

Adaptability and Change Management: The business environment is dynamic; therefore, organizations must be willing to adapt their strategies in response to market changes, technological advancements, or shifts in consumer preferences. Effective change management processes help facilitate smooth transitions.

Stakeholder Engagement: Engaging with stakeholders (employees, customers, shareholders, and the community) is vital for gaining support and ensuring that the strategies meet the needs and expectations of those affected by organizational decisions [4].

Sustainable Competitive Advantage: The ultimate goal of strategic management is to create and maintain a competitive edge in the marketplace. This can be achieved through innovation, superior customer service, unique value propositions, or operational efficiencies.

We will analyze the stages undertaken in the strategic planning process and detail how strategic management is applied and its benefits.

One of the most important aspects of strategic management refers to anticipating the factors that will have an impact on the organization in the future. Some of these cannot be changed, while upon others, the organization can intervene. To be effective, an organization must ensure that there is a certain level of alignment between what it can offer and what the world needs, and that is why it is important to talk about the analysis of internal and external trends.

It is extremely important to analyze what microenvironment and macroenvironment mean for the subject addressed, the P.E.S.T. Model, M. Porter's "5 Forces Model," and SWOT.

SWOT Analysis - In-Depth

- **Actionable Insights:** After conducting a SWOT analysis, organizations can create strategic initiatives based on the findings. For example, they might leverage strengths to capitalize on opportunities or develop plans to address weaknesses that make them vulnerable to threats.
- **Team Involvement:** Engaging various stakeholders in the SWOT analysis can provide diverse perspectives, leading to a more comprehensive understanding of the organization's position.

PESTEL Analysis - Detailed Applications

- Trend Monitoring: By regularly conducting PESTEL analyses, organizations can stay ahead of trends and shifts in the external environment, allowing for proactive strategic adjustments [5].
- Risk Management: Understanding potential political or economic changes helps organizations anticipate risks and devise mitigation strategies [6].

BCG Matrix - Portfolio Management

- Resource Allocation: The BCG Matrix not only helps in deciding which products to invest in but also in determining when to divest or discontinue products that fall into the "Dogs" category.
- Strategic Focus: Organizations can use the matrix to ensure that their portfolio aligns with their overall strategic goals, balancing risk and return effectively [7].

Balanced Scorecard - Comprehensive Performance Measurement

- Alignment: The Balanced Scorecard helps ensure that all levels of the organization are aligned with the strategic objectives, enhancing coherence in action.
- Continuous Improvement: By regularly reviewing performance metrics, organizations can identify areas for improvement and adjust their strategies accordingly [8].

Key Performance Indicators (KPIs) - Tracking Success

- SMART Criteria: KPIs should be Specific, Measurable, Achievable, Relevant, and Time-bound to ensure they effectively track progress toward strategic goals.
- Feedback Loop: Integrating KPI results into regular reviews creates a feedback loop that informs future strategic decisions.

Feedback Mechanisms - Stakeholder Involvement

- Customer Feedback: Actively seeking customer feedback through surveys or focus groups can inform product development and service enhancements.
- Employee Engagement: Encouraging employee feedback fosters a culture of open communication, which can lead to valuable insights for improving operational efficiency and morale.

Porter's Five Forces Model:

- This model helps analyze the competitive forces within an industry, providing insights into the overall industry structure and profitability. The five forces include:
 - Threat of new entrants.
 - Bargaining power of suppliers.
 - Bargaining power of buyers.

- Threat of substitute products or services.
- Rivalry among existing competitors.
- Application: By understanding these forces, organizations can better position themselves strategically within their industry [9].

Analysis, as well as the analysis of the organization's competencies. As full members with rights and obligations in NATO and EU structures, we have the obligation to research and align international decisions. In this sense, we cannot discuss only national strategies in this branch of the industry. In this section, we aim to analyze the international strategy that impacts us and which can generate numerous development opportunities as well as restrictive aspects for the armaments industry. We will analyze NATO and NIAG meetings and study the international geopolitical and legislative framework, conducting an analysis of Romania and the Romanian industry's position in the international context.

It is crucial for an argumentative paper to consult public NATO, MoE (ME), MoD (MAPN) documents and international statistics in the development of a strategic management plan. In addition to these documents, we will participate in multiple international meetings in the field from which we will obtain documents for our research.

Our research also aims to analyze everything that the defense industry in Romania entails between the past and the present, drawing a parallel based on existing public documents, both in specialized writings and in the presentation of companies in the armament industry, their overall thinking in a synergistic context. This aspect can briefly present an overview of what we can offer, in terms of supply and demand, as well as a general presentation starting from the mission, objectives, and marketing policies promoted individually at the industry branch level. As I mentioned, we will present the current situation from an economic perspective and the representativeness of the products in NATO product catalogs, as well as their demand at the European level. The proposed analysis also aims to draw a parallel between the products offered before 1989 and after that year, and we will try to identify what this production means today in the international context. As a research method, we will use both documentary research based on the MoD (MAPN) library and applied research, meaning we will utilize exact offers collected from each factory by participating in multiple international profile exhibitions and fairs. It is important to gather the information as it is in reality as well as in comparison with international standards.

As I stated, it is important for strategic management to identify the mission of the industry, strategic objectives, strategic options, resources, timelines, synergy, competitive advantage or distinctive competence, as well as the current regulations that can benefit or disadvantage this branch of the industry because there is a national strategy in place. It operates with an extended concept of national security,

in accordance with European principles. Today, there are multiple interests converging towards ensuring national security.

Apart from elements related to defense, public order, or intelligence and counterintelligence activities, security can no longer be separated today from a competitive economic environment, financial-budgetary stability, the existence of public systems—education, health, pensions—that are functional and adapted to changes, the protection of critical infrastructures, or the capacity to respond to environmental issues. It is timely, and we will discuss the existing priorities within the legislative framework in Romania for the armaments industry, including general and specific objectives, as well as opportunities and threats. It is vital to understand where we are and where we want to go. We cannot discuss research if we do not discuss verification indicators, construction plans, and the importance of researching and innovating competitive products. We will use as a research methodology national interest documents (NATIONAL STRATEGY FOR THE DEFENCE INDUSTRY) as well as estimation and strategy documents aimed at ensuring a national security climate. All documents and information used will be verified by an S.S department – Information Security Structure, so that the documents used for research do not contain classified information.

III. Conclusion. Strategic Management for the Relaunch of Romania's Armaments Industry in the New International Context

This research in strategic management for the relaunch of Romania's armaments industry, through the analyses conducted and the intersection of the obtained results, will outline a strategy for the upcoming period. for this branch of the industry. As proposals, we will try to encompass what strategic management means by addressing, both the parts mentioned in theory and forecasts. The approach to security and the management of crisis situations applied in practice, in terms of the armament industry branch in Romania, will bring new challenges to our work, reintroducing crisis management methods at every level of production, supply chains, and distribution, as well as the channels for their implementation.

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NEW TECHNOLOGIES FOR EFFICIENT AND APPROPRIATE URBAN WASTE MANAGEMENT

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Abstract

Urban waste management is a major challenge for contemporary cities, affecting the environment, public health and the economy. This article analyses the impact of new technologies, such as Io T, artificial intelligence, automation and digitalization, on the efficiency of waste collection, sorting and recycling systems. Modern solutions and relevant case studies are presented, highlighting the role of innovation in the transition towards a circular economy and a sustainable urban environment. The paper underlines the need to adopt technology in public policies to transform waste management into a smart, efficient and environmentally friendly process.

Keywords

Urban waste; artificial intelligence; innovation; recycling systems.

I. Introduction

In recent decades, accelerated urbanization, population growth and lifestyle changes have led to a significant increase in the amount of waste generated in the urban environment. Urban waste is not only an environmental challenge, but also

an economic and social one, affecting public health, quality of life and the sustainability of cities.

Traditionally, waste management systems have been based on unsorted collection and landfilling, methods that are no longer viable in the current context. They generate high costs, greenhouse gas emissions, soil and groundwater pollution, but also major risks to health and the environment. In addition, many cities face a lack of space for new landfills, outdated infrastructure and insufficient selective collection [1].

Daily waste generation per capita in high-income countries is projected to increase by 19% by 2050, compared to low- and middle-income countries, where it is expected to increase by around 40% or more. The total amount of waste generated by low-income countries is expected to increase more than threefold by 2050 [2]. The East Asia and Pacific region generates most of the world's waste, about 23%, and the Middle East and North Africa region produces the least in absolute terms, about 6%. However, the fastest growing regions are Sub-Saharan Africa, South Asia, the Middle East and North Africa, where, by 2050, total waste generation is expected to double and even triple [3].

In this context, technology becomes an essential ally in the transition to an efficient, sustainable and digitized waste management system. The emergence of innovative solutions such as the Internet of Things (IoT), artificial intelligence (AI), collection automation, smart sorting and digital applications opens up new perspectives in addressing this global problem.

However, while such technologies are widely discussed in policy and academic literature, systematic methodologies for evaluating their real impact remain limited. The aim of this research is to analyse the main emerging technologies that contribute to a more efficient and appropriate waste management in the urban environment by answering the following research question: „How can emerging digital technologies, such as IoT, AI, and blockchain, be systematically evaluated and integrated to improve the efficiency, environmental performance, and sustainability of urban waste management systems?”

The paper aims to highlight both the benefits of these technologies and the current limitations of conventional systems, while providing concrete examples of good practices at the international level.

To answer this question, the study combines statistical and policy data with selected case studies illustrating good practices in technologically advanced waste management. The following section details the methodological framework adopted for data selection, integration, case study analysis, and technology assessment, while also identifying the limitations and future research needs of the study.

II. Methodology

A. Research Design and Data Sources

This study adopted a mixed-method research design, integrating both qualitative and quantitative components to capture the complexity of waste management systems and their technological transformations. The purpose was to link empirical data (such as waste generation rates and recycling performance) with policy frameworks and technological innovations influencing operational practices.

The quantitative aspect of the research was based on secondary data extracted from official and validated sources such as Eurostat, the European Environment Agency (EEA), the World Bank, and the European Parliament's Waste Statistics database. These datasets were chosen for their methodological consistency, cross-national comparability, and coverage of key indicators, including municipal waste per capita, recycling and landfilling rates, and waste treatment distribution. The timeframe for data selection (2006–2024) was designed to capture both long-term trends and the recent acceleration of technological adoption.

The qualitative aspect was grounded in an extensive literature review covering peer-reviewed academic publications, European Union directives, and technical reports from waste management agencies. The purpose was to contextualize the statistical trends within broader policy and innovation dynamics, and to identify emerging technologies relevant to the urban waste sector. The literature review followed a systematic selection protocol: (1) identification of sources using keywords such as “smart waste management,” “IoT,” “AI sorting,” “circular economy,” and “urban sustainability”; (2) inclusion of documents published between 2015 and 2024; and (3) exclusion of sources lacking methodological transparency or empirical grounding.

Data were processed and visualized using Microsoft Excel to generate comparative charts and trends (Figures 1-3). This allowed for an integrated understanding of both macro-level statistical dynamics and micro-level technological applications.

B. Case Study Selection and Evaluation

In this study, three representative cases were selected: (1) smart containers equipped with IoT sensors, (2) AI-based waste sorting systems, and (3) GPS and IoT-driven route optimization platforms. These examples were chosen through a purposive sampling strategy, guided by inclusion criteria grounded in academic rigor and policy relevance. The selection criteria included:

- Operational relevance: The case had to address one of the main stages in waste management, collection, sorting, or transportation.

- Empirical documentation: The initiative needed to be supported by published data, technical evaluations, or publicly available project results.
- Transferability potential: The model had to demonstrate applicability or scalability in other urban or regional contexts, particularly within the European Union.

Each case study was examined through a multi-criteria evaluation framework, assessing four key dimensions: Efficiency improvement (reduction in operating time, resource use, or costs); Environmental performance (measurable decrease in landfill use, emissions, or contamination); Economic feasibility (analysis of initial investment versus long-term savings); Scalability and technological maturity (readiness level for large-scale implementation).

For example, smart containers were evaluated based on reported improvements in collection frequency and fleet utilization efficiency, while AI-based sorting systems were examined for their increased purity rates in recyclables and operational accuracy. Route optimization cases were analyzed for their ability to lower fuel consumption and CO₂ emissions through predictive algorithms. The synthesis of these cases provided practical validation of the broader theoretical and policy discussions presented in earlier sections, demonstrating the real-world value of emerging waste management technologies.

C. Technological Assessment Framework

To systematically evaluate the technologies identified (IoT, AI, blockchain, robotics, and automation), a multidimensional assessment framework was designed, combining economic, environmental, social, and regional dimensions. This structure was inspired by the European Commission's Digital Europe Programme evaluation criteria and adapted for urban waste management applications.

The economic dimension focused on the cost-benefit relationship and return on investment (ROI). Data on operational savings, reduced downtime, and optimized logistics were used to estimate long-term efficiency gains relative to initial capital investment. In cities where IoT-enabled bins or AI sorting lines have been implemented, studies report cost reductions of 15–30% in logistics operations, validating the importance of this metric.

The environmental dimension evaluated each technology's potential to reduce greenhouse gas emissions, improve recycling rates, and decrease landfill dependency. Life Cycle Assessment (LCA) principles were used qualitatively to assess environmental implications.

The social and institutional dimension captured factors of public acceptability, user engagement, and institutional readiness. Successful technology adoption is strongly correlated with digital literacy, environmental awareness, and the presence of local governance frameworks that support innovation.

Finally, the regional adaptability dimension considered infrastructural capacity and policy alignment across different European regions. For instance, blockchain traceability solutions might be more readily adopted in high-income urban centers with advanced digital infrastructure than in smaller municipalities with limited resources.

This multidimensional evaluation allowed for a holistic comparison of emerging technologies, identifying both synergies (e.g., IoT + AI integration for predictive collection) and barriers (e.g., cost and interoperability issues).

III. State of Art of Urban Waste Management

Urban waste management is one of the most pressing challenges facing modern cities. Against the background of the rapid growth of the urban population and the intensification of economic activities, the volume of waste generated daily has reached alarming levels. According to Eurostat data, in the European Union, each citizen generates an average of between 450 and 600 kg of municipal waste annually, and a large part of it comes from urban areas. Globally (fig.1), the states that produced the largest amount of municipal waste are: the USA with 265.2 million metric tons, followed by China with 215.2 million metric tons and Germany with 53.7 million metric tons (at the level of 2021).

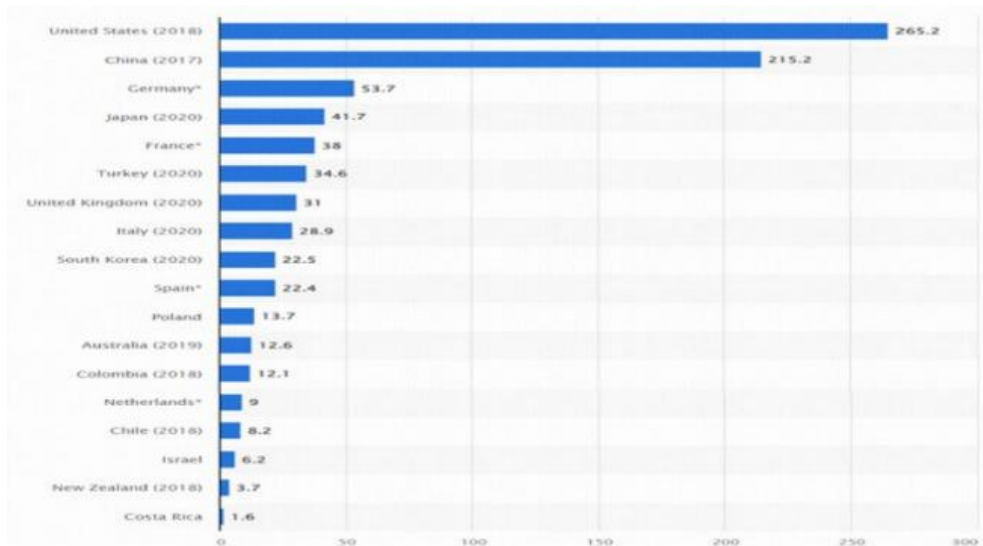


Fig. 1. Situation of municipal waste-generating states in 2021 [2]

At the European Union level, the average amount of municipal waste measured per capita increased in the EU, from 2006 to 2021. Although municipal waste per capita has increased in most EU countries, it has decreased in countries such as

Malta, Cyprus, Spain and Romania (fig. 2). As with the global trend, richer countries tend to produce more waste per capita.

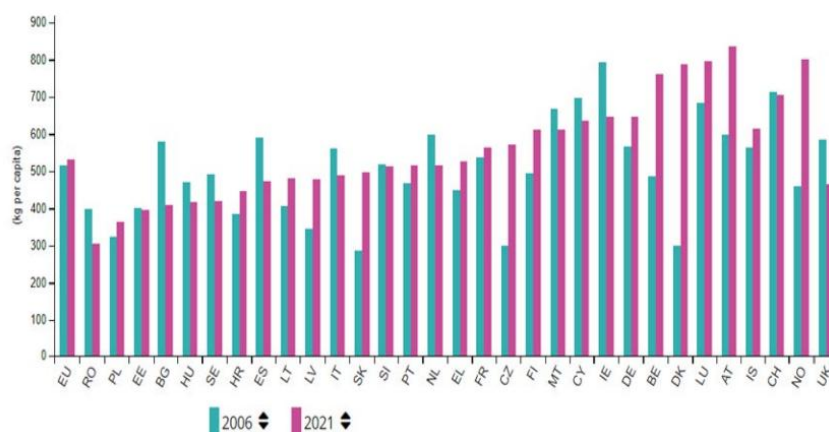


Fig. 2. Municipal waste generated in Europe in 2006 and 2021.[2]

According to data published on the European Parliament's website, 2.2 billion tonnes of waste are generated in the EU every year. About 27% of municipal waste is collected daily and treated by municipalities, mainly generated by households. Around 39.2% of waste was recycled and 32.2% landfilled in the EU in 2020. [3]

In the absence of efficient selective collection, these types of waste often end up mixed in the landfill, considerably reducing the possibility of recycling or energy recovery. In many cities in Romania and other parts of the world, waste management systems are still based on conventional methods:

- *Periodic unsorted collection* – waste is collected in a single container, without sorting at source;
- *Landfill storage* – the most used method, but with a major impact on the environment and public health;
- *Incineration* – used in some European cities, but with risks in terms of pollutant emissions if not properly controlled.

Although some municipalities have introduced containers for separate collection, the recycling rate remains low, mainly due to a lack of environmental education, adequate infrastructure and an effective monitoring system. Among the main problems of current urban waste management systems are:

- *Overcrowding of landfills* – many landfills are close to their maximum capacity;
- *Lack of efficient selective collection* – most recyclable waste is not recovered;
- *High operating costs* – transporting, collecting and storing waste involves considerable financial and logistical resources;

- *Negative impact on the environment* – greenhouse gas emissions, soil and groundwater pollution;
- *Environmental crime* – illegal dumping, uncontrolled burning, and lack of traceability of waste.

Technological advances have also significantly improved the efficiency of waste collection. Many waste management companies are currently using GPS tracking systems on their collection vehicles to optimize routes and schedules, reducing fuel consumption and emissions [4]. In addition, sensor-equipped smart bins alert collection teams when they are full, preventing overfilling and ensuring timely waste removal. These innovative technologies streamline waste collection processes and help to monitor and manage waste levels more effectively, leading to a cleaner, greener environment.

New initiatives, such as community composting systems and reusable waste collection bags, further reduce the environmental impact of waste disposal. These improvements not only benefit the environment, but also contribute to the creation of more sustainable and livable communities for future generations [5].

Optimising waste collection routes and programmes is essential for modern waste management in urban areas. By effectively using advanced technologies such as GPS tracking and route-planning software, local authorities can increase operational efficiency, reduce costs, and lessen the environmental impact of waste transport [6].

Implementing smart waste collection solutions, such as sensors that monitor bin fill levels and notify collection teams when bins need to be emptied, further improves waste management practices.

Smart waste collection systems are transforming waste management in urban areas. These innovative systems use technologies such as sensors and data analytics to optimize the collection process, reducing costs and improving efficiency. By monitoring waste levels in bins in real-time, these systems can only schedule collection when bins are full, minimizing unnecessary lifts and reducing carbon emissions from collection vehicles.

IV. Emerging Technologies in Waste Management

Technology is playing an increasingly important role in the transition to a more efficient, sustainable and intelligent waste management system. In recent decades, digitalization, automation and artificial intelligence have opened new directions for optimizing waste collection, sorting and recovery. This chapter presents the most relevant emerging technologies applied in the municipal waste sector.

Modern technology is becoming an essential component in addressing the growing challenges of waste management in smart cities. This is also influenced by

the growing demand for efficient, environmentally friendly and sustainable waste management solutions.

The main way in which IoT makes its presence felt is by incorporating smart devices and sensors into the urban landscape, tasked with monitoring and collecting waste data [4]. With a data-centric approach, this system allows for more efficient management of waste collection and disposal, transport logistics and recycling efforts. The waste management system can use integrated tracking and data sharing technologies, thus optimizing processes specific to the waste life cycle, such as collection, recovery and prevention of waste generation.

An IoT-based waste management system (fig. 3) comprises smart garbage containers equipped with sensors that monitor their fill level, allowing waste management and analysis in real time [6]. Data from these bins can then be transmitted wirelessly to a central hub, facilitating prompt waste collection and preventing overflow. The sensors installed in these systems also measure the weight and level of waste inside the trash can, communicating this information to waste management systems. This technological amalgam, with blockchain that provides traceability, transparency and audit features in a decentralized and secure manner, is proving essential in improving waste management.

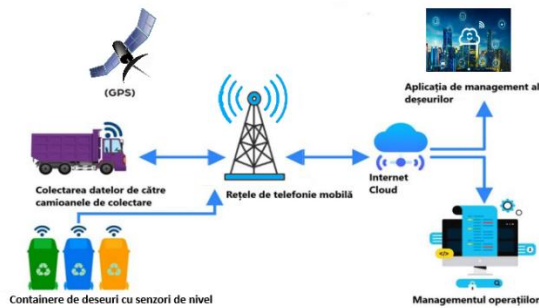


Fig. 3. General architecture of an intelligent waste management system

Long-range network (LoRaWAN) technology is a key technology for IoT architectures. This technology can support various services within the smart waste management system, including smart bins and storage containers that interact with users, as well as video surveillance units equipped with machine learning capabilities that can, for example, detect a potential fire.

Smart bin technology uses artificial intelligence to redirect waste efficiently, with minimal labor consumption and the lowest degree of traffic congestion. A smart basket can be made by combining several technologies, such as Artificial Intelligence of Things (AIoT), computer vision, robotics, RFID tags, near field communication (NFC), sensors, wireless sensor networks, compactors, actuators, smart monitoring systems, and dashboards. Thus, information about recyclable

materials can be received directly by integrating the smart bin with a dashboard for real-time monitoring. Landfill companies can thus streamline their workflows and reduce the time it takes to check trash cans by using monitoring indications [7].

AI-based waste sorting technologies use equipment and software that use image analysis to sort recyclables with a much higher accuracy and recovery rate than conventional systems.

New technologies offer significant potential for the modernization of urban waste management systems. From automated collection and sorting to the integration of artificial intelligence and mobile apps, cities can become cleaner, more efficient, and more sustainable. However, implementing these solutions requires investment, collaboration between the public and private sectors, and the active involvement of citizens.

V. Limitations and future research

Despite its structured approach, this study acknowledges several limitations. The most significant constraint lies in its dependence on secondary data, which, although reliable, may not capture the full variability of local contexts or recent pilot projects. Differences in national reporting standards and temporal inconsistencies among datasets can also affect cross-comparability.

The case study component, while illustrative of best practices, does not constitute a statistically representative sample of all technological innovations in waste management. Each example reflects a specific local context and may not be generalizable to regions with different socio-economic or infrastructural conditions. Moreover, the absence of fieldwork or direct stakeholder interviews limits the empirical depth of the analysis, particularly concerning user behavior and organizational change.

Future research should therefore pursue empirical validation of the proposed evaluation framework through pilot testing, participatory observation, and cost-environmental modeling. Combining technical analysis with social research methods would offer a more comprehensive understanding of how technology can transform urban waste management toward sustainability.

VI. Conclusions

Urban waste management is one of the major challenges of modern society, especially in the context of accelerated urbanization and increased consumption. From the analysis carried out in this article, it is clear that traditional collection and storage methods are no longer enough, and the transition to a smart and sustainable model is not only necessary, but urgent.

New technologies, such as IoT sensors, artificial intelligence, collection automation, mobile apps and digital platforms, contribute significantly to optimising the entire waste management chain. These solutions not only streamline operational processes and reduce costs, but also bring important environmental benefits, by increasing the recycling rate, reducing pollution and actively involving citizens in waste sorting.

The transition to a modern system is possible and often brings tangible results in the short term. However, the success of these technologies depends on key factors such as political will, strategic investments, infrastructure development, and public environmental education.

In conclusion, the cities of the future will be those that adopt these innovative technologies early, transforming waste management from a chronic problem into an opportunity for sustainable, efficient and intelligent development.

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INTEGRATION OF VIBROTACTILE STIMULATION AND EEG ANALYSES FOR OPTIMIZING AUDITORY PROCESSING AND POSTURAL BALANCE IN USERS OF COCHLEAR IMPLANTS AND HEARING AIDS

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Abstract

This article presents a structured approach to the development of a vibrotactile wristband intended to improve speech comprehension and postural control in users of cochlear implants and hearing aids. Making use of the principles of multisensory integration and sensory substitution, this study reviews relevant literature, outlines methodological plans, and forecasts the impact of associating auditory and somatosensory stimuli for dual therapeutic benefit. The proposal seeks to bridge the gap in current assistive technologies by introducing a compact, wearable device capable of delivering speech-synchronized vibrotactile feedback in daily listening environments.

Keywords

Vibrotactile stimulation; cochlear implants; hearing aids; postural control; multisensory integration.

I. Introduction

Hearing loss is a major global health concern affecting an increasing number of individuals across all age groups. Beyond impairing communication, hearing loss has been linked to deficits in postural stability and spatial orientation. While cochlear implants and hearing aids have significantly improved speech perception and environmental awareness, they do not fully resolve difficulties in noisy environments or vestibular-related deficits.

The intersection between auditory and balance functions has gained attention in recent years, with studies showing that a decline in hearing is often accompanied by balance impairments and increased fall risk. Given the shared neurophysiological pathways and proximity of auditory and vestibular systems in the inner ear, it is essential to adopt a multisensory approach to rehabilitation.[1]

This research proposes a wearable solution, a vibrotactile wristband, that aims to provide auditory enhancement and improve postural stability simultaneously. The wristband delivers vibrotactile stimulation synchronized with the rhythm of speech. It is designed for daily use, at-home use and targets adult and child users of cochlear implants and hearing aids. The ultimate objective is to validate whether such stimulation improves speech-in-noise recognition and reduces sway in posture-graphic analysis, while also monitoring cortical responses through EEG analysis to better understand the neurophysiological effects of multisensory integration. If successful, this approach could introduce a paradigm shift in audiological rehabilitation and non-invasive technology.

The innovation in this study lies not only in the integration of vibrotactile stimulation with auditory input, but also in its ergonomic, user-friendly format suitable for real-world use. By combining two core rehabilitation goals: speech comprehension and postural control, the wristband provides a dual solution that may enhance patient outcomes and reduce reliance on fragmented therapeutic protocols.

Additionally, this research contributes to the growing field of wearable health technology, offering an interdisciplinary model that merges audiology, neuroengineering, and human factors. Insights from the pilot study will help refine both the technical design of the device and the therapeutic strategies employed in clinical audiology.

To support the validation of the dual impact of the proposed vibrotactile wristband, the study also incorporates electroencephalographic (EEG) monitoring to observe neurophysiological responses associated with auditory and somatosensory integration. EEG analyses will be used to assess neural entrainment to speech rhythm and to detect changes in cortical activity patterns before and after vibrotactile stimulation. This approach adds an objective neurophysiological perspective to the evaluation of the device's efficacy, offering deeper insights into how multisensory feedback may modulate central auditory and balance processing. Such findings could inform future rehabilitation protocols, supporting more personalized and integrative strategies for individuals with combined auditory and vestibular deficits.

Our study addresses a current gap: there is no integrated, real-world wearable that targets both auditory and balance outcomes in cochlear implant and hearing aid users while concurrently quantifying cortical dynamics. We therefore pursue the aims: test whether a week of speech-synchronized vibrotactile stimulation improves

word recognition in noise and reduces postural sway; and determine whether EEG indices of audio-tactile entrainment change alongside behaviour. By unifying dual rehabilitation goals within an ergonomic device and validating outcomes across behavioural and neural levels, this work seeks to advance multisensory, at-home audiological rehabilitation.

II. Methodology

This study is structured into several phases: literature review, prototype development, participant recruitment, experimental testing, data analysis and results interpretation. This research is currently in its early developmental stage and is being prepared within the Laboratory of the Faculty of Product Design and Environment, Transilvania University of Brasov, Romania. Ethical approval will be requested from the University's Research Ethics Committee prior to participant recruitment (approval number pending). All participants, or their legal tutors in the case of minors, will provide written informed consent in accordance with the Declaration of Helsinki.

A. Literature Foundation

Multisensory integration, particularly the interaction between auditory and tactile modalities, has emerged as a promising field for enhancing speech perception and balance control for individuals with hearing loss. Huang showed that cochlear implant users had significantly improved speech recognition in noise conditions when vibrotactile stimuli were temporally align with auditory input [2]. Luo further supported this by demonstrating enhanced melody recognition for cochlear implant users through vibrotactile stimulation [4]. Fu and Riecke provided EEG based evidence of neural entrainment during audio-tactile integration, confirming that synchronized stimuli across modalities may optimize auditory temporal resolution [5],[6]. Beyond auditory enhancement, the integration of somatosensory stimuli has shown considerable impact on balance and postural control. Some studies reported that somatosensory rehabilitation techniques led to improved postural stability in children with hearing loss and vestibular dysfunction [4]. Similarly, Choi observed that vibrotactile feedback improved balance performance in elderly participants, reinforcing the relevance of tactile cues in proprioceptive and vestibular compensation [4].

Several additional studies strengthen the theoretical foundation of this study. Fletcher demonstrated that electro-haptic stimulation could significantly improve spatial hearing and localization for cochlear implant users, highlighting the effectiveness of wearable multisensory plasticity in cochlear implant users and emphasizing the importance of incorporating visual and tactile cues into

rehabilitation strategies [6]. Furthermore, he investigated the long term impact of subconscious vibrotactile stimulation in patients with bilateral vestibulopathy and found substantial improvements in mobility and balance that persisted over two years [6].

These findings are reinforced by foundational neuroscience research. Gick and Derrick demonstrated that aero-tactile stimulation could directly modulate speech perception in normal hearing individuals, supporting the presence of early multisensory integration mechanisms in speech processing [7]. Deneber also showed modulation of auditory evoked potentials after cochlear implantation, indicating neuroplastic adaptation that could facilitate tactile-auditory synergy [8].

Taken together, these studies provide a robust foundation for the development of multisensory therapeutic tools, such as the proposed vibrotactile wristband, aimed at improving both speech-in-noise comprehension and balance in cochlear implant and hearing aid users. They support the hypothesis that synchronized tactile feedback can stimulate neuroplastic reorganization in auditory and postural control pathways. [17-20]

B. Prototype Description

The proposed vibrotactile wristband prototype is currently in the early design stage and aims to transform acoustic information into synchronized tactile feedback to support multisensory rehabilitation. The system is conceived as a compact, wearable device capable of translating speech rhythm or spectral cues into tactile stimulation on the wrist.

The prototype will operate as a closed-loop audio-tactile system. An onboard digital microphone will capture incoming sounds (speech or environmental noise, which will then be processed by a microcontroller unit (Arduino Nano or Raspberry Pi Pico W). The signal will undergo either temporal envelope extraction or spectral band mapping, depending on the test condition, to generate vibration control patterns. These processed signals will drive miniature vibrotactile actuators (coin vibration motors) embedded within the wristband, delivering rhythmic pulses synchronized with the acoustic input. The resulting tactile feedback will allow users to perceive temporal speech structure through vibration pattern aligned to syllabic rhythm. Power will be supplied by a rechargeable Li-ion battery, ensuring portability and daily usability. A Bluetooth module will enable wireless configuration, parameter adjustment and real-time data transmission for experimental monitoring. To maintain temporal precision between auditory and tactile events, a real-time clock module will be implemented within the signal processing loop. [Fig. 1]

From an ergonomic standpoint, the wristband will be made of hypoallergenic silicone and include an adjustable strap to ensure comfort during long wear. All

vibrotactile outputs will remain safe tactile thresholds to prevent sensory fatigue or discomfort. The prototype’s physical design will prioritize low weight (<100 g) and user autonomy during daily listening sessions.

Schematic representation of the system (Fig.1):

Audio Input (Microphone) → Signal Processing (MCU) → Envelope Extraction/ frequency band mapping → Vibration Control Signal → Vibrotactile Actuators → User Feedback.

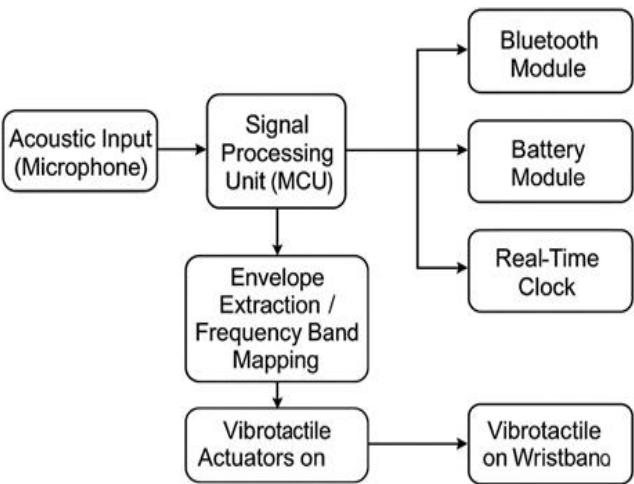


Fig. 1. Functional diagram of the vibrotactile wristband prototype

Table 1. Prototype Elements for Multisensory Stimulation

Component	Description	Role
Audio Input	Digital Microphone	Captures the acoustic signal
Microcontroller Unit (MCU)	Arduino Nano/ Raspberry Pi Pico W	Processes input
Vibrotactile Actuators	Coin vibration motors	Synchronized tactile feedback
Power Supply	Rechargeable Li-ion battery	Powers the system
Bluetooth Module	Wireless module	Allows remote configuration
Real time Clock/ Sync System	Timing module	Maintains temporal accuracy of signals
Enclosure and Wristband	Wearable housing with adjustable strap	Ensures portability

C. Participants

The study is designed as pilot investigation including twenty participants (12 females, 8 males) aged 15-70 years. All participants will present unilateral or bilateral sensorineural hearing loss and will be fitted with either cochlear implant or hearing aids. Individuals will be recruited from the clinical database of a private audiological clinic. Inclusion criteria include at least six months of auditory device use and stable audiometric thresholds. Exclusion criteria involve severe neurological, vestibular or musculoskeletal disorders that could affect postural control.

D. Experimental Protocol

- Pre-test: speech-in-noise tonal and vocal audiometry using bisyllabic words (65 dB SPL + 60 dB noise); postural analysis on Kistler platform in eyes open/closed conditions.
- Intervention: subjects will wear the wristband daily for seven days during 30 minutes passive listening sessions (audiobooks and conversation recordings).
- Post-test: repetition of audiometry and posturography.

E. Data Analysis

As the study is currently at an early planning stage, data analysis methods are outlined here for the future implementation. Pre- and post- intervention scores for word recognition in noise and postural sway parameters will be compared within subjects using paired-sample t-tests. Effect sizes will be reported to quantify the magnitude of observed changes. EEG data will be processed using MATLAB and EEGLAB to extract spectral power and phase locking values in theta (4-7 Hz) and beta (13-30 Hz) frequency bands. A repeated-measures ANOVA will be conducted to assess potential changes in neural entrainment before and after vibrotactile exposure. These analyses aim to provide objective confirmation of multisensory integration effects once empirical data become available.

The innovation in this study lies not only in the integration of vibrotactile stimulation with auditory input, but also in its ergonomic, user-friendly format suitable for real-world use. By combining two core rehabilitation goals (speech comprehension and postural control) the wristband provides a dual solution that may enhance patient outcomes and reduce reliance on fragmented therapeutic protocols. Insights from the pilot study will help refine both the technical design of the device and the therapeutic strategies employed in clinical audiology.

III. Results and Discussion

As the practical phase is in progress, this section outlines anticipated outcomes based on existing studies. The dual function of the wristband aims to bridge the gap between conventional rehabilitation approaches that treat hearing and balance separately.

A. Expected Speech and Postural Results

Previous studies showed speech-in-noise improvements of up to 15%. We expect comparable effects, which will be quantified through bisyllabic word recognition tests before and after exposure. Likewise, postural data are expected to show reductions in sway path length and velocity, consistent with Choi, who observed comparable balance enhancements following vibrotactile feedback in older adults. [1],[4], [5],[11].

Balance improvements are expected in sway path metrics, especially under eyes-closed conditions [10]. This would confirm that supplemental vibrotactile stimulation can improve proprioceptive feedback and posture control.

B. Integration and Usability

User feedback will be collected to assess wearability, comfort, and daily use. Limitations include potential tactile habituation, individual variability in sensitivity, and difficulty isolating variables in a complex clinical environment. The innovation in this study lies not only in the integration of vibrotactile stimulation with auditory input, but also in its ergonomic, user-friendly format suitable for real-world use. By combining two core rehabilitation goals (speech comprehension and postural control) the wristband provides a dual solution that may enhance patient outcomes and reduce reliance on fragmented therapeutic protocols.

The study aligns with current efforts to integrate wearable technology into hearing rehabilitation, combining engineering design with clinical feedback from audiology practice.

C. Expected EEG Findings

Since the project is currently in its initial phase and EEG data collection has not yet begun, the following results are theoretically anticipated. Based on previous literature, vibrotactile stimulation synchronized with speech rhythm is expected to enhance neural entrainment in auditory cortical areas, reflected by increased theta-band phase-locking values and improved temporal coherence between auditory

and tactile signals. Once data collection is completed, statistical comparisons will be performed to confirm whether these patterns are observed empirically.

D. Comparative Analysis of Multisensory Technologies

A comparative review of multisensory approaches in audiological rehabilitation was integrated to contextualize the novelty of this research. Electro-haptic stimulation has demonstrated efficacy in enhancing spatial hearing, while mechanical stimulation devices are often simpler but less adaptable. In contrast, the proposed wristband combines rhythmic vibrotactile cues with ergonomic design and EEG monitoring, offering real-time feedback and multisensory synchronization. Table 2 presents a summarized comparison.

Table 2. Comparison of Multisensory Stimulation Approaches

Technology	Advantages	Limitations
Electro-haptic systems	High precision; spatial localization aid	Energy- intensive; complex integration
Mechanical stimulation	Low-cost; easy to implement	Limited encoding flexibility
Vibrotactile wristband	Rhythmic, intuitive; wearable; EEG linked	Requires calibration; user-dependent

This comparison reinforces the potential of the proposed solution to deliver an accessible and integrative alternative with broad clinical applicability. By combining technological flexibility with user centered design, the wristband addresses both clinical and functional expectations. Further comparative studies are needed to quantify long term benefits across different patient profiles.

E. Implementation Challenges and Limitations

Potential barriers to long-term implementation include user habituation to tactile input, inter-individual differences in sensitivity thresholds, and variability in daily use compliance. The device’s usability may also be affected by comorbid conditions or dexterity limitations. Future versions of the system will include personalized calibration algorithms and optional remote monitoring through Bluetooth modules.

IV. Conclusions

This study outlines an interdisciplinary approach to audiological and vestibular rehabilitation by combining vibrotactile stimulation with auditory input in a wearable format. The wristband prototype was designed to address two key challenges (enhancing speech comprehension in noisy environments and improving postural stability) through synchronized multisensory feedback. Drawing on existing literature, the concept shows promising therapeutic potential, and the study will further validate its impact through pilot studies targeting both auditory and motor performance outcomes. The compact design supports daily use and encourages user autonomy, especially in patients using cochlear implants or hearing aids.

Looking forward, we plan to optimize signal processing algorithms, refine the system's adaptability to individual sensory profiles, and investigate its applicability in pediatric rehabilitation contexts. To enhance clinical supervision and individualized treatment planning, real-time monitoring will be implemented via digital tracking and cloud-based feedback systems. We believe this approach can streamline current rehabilitation procedures by combining two therapies, auditory and balance, into a single, user-friendly system.

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WAR AND WIND: OCCUPATIONAL RISK AND SAFETY MANAGEMENT IN CONFLICT-AFFECTED RENEWABLE ENERGY PROJECTS

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Abstract

This article explores the intersection of occupational safety and renewable energy development in conflict-affected regions. As global demand for clean energy rises, wind and solar projects are increasingly deployed in politically unstable or post-conflict zones. These environments pose unique risks to workers, from physical threats due to violence to psychological stress and logistical challenges. This study investigates how occupational risk is assessed and managed in such contexts, drawing on case studies, interviews, and safety frameworks. It proposes a conflict-sensitive safety management model tailored to renewable energy infrastructure.

Keywords

Safety; renewable energy; risks; psychological stress.

I. Introduction

Background and Rationale. The global transition to renewable energy is accelerating, driven by the urgent need to mitigate climate change, reduce dependence on fossil fuels, and promote sustainable development. Wind, solar, and hybrid energy systems are increasingly deployed not only in stable regions but also in fragile and conflict-affected areas where energy access is limited or disrupted [1]. These projects are often supported by international development agencies, humanitarian

organizations, and private investors seeking to rebuild infrastructure and foster resilience in post-conflict societies [2]. However, the deployment of renewable energy infrastructure in conflict zones introduces a complex array of occupational risks. Workers in these environments face not only the conventional hazards associated with construction and energy systems, such as electrical accidents, falls, and equipment failure, but also risks amplified by political instability, violence, and weak institutional oversight [3]. These include threats from armed groups, unexploded ordnance, psychological trauma, and disrupted supply chains. Despite these challenges, there is a notable gap in the academic literature and policy frameworks addressing occupational safety in such high-risk contexts [4].

Problem Statement. While occupational health and safety (OHS) is a well-established field in industrialized settings, its application in conflict-affected renewable energy projects remains underexplored. Existing safety protocols often fail to account for the dynamic and volatile nature of conflict environments, where standard risk assessments may be inadequate or inapplicable [5]. Moreover, the intersection of conflict dynamics, local labor practices, and international project management creates a unique and urgent need for context-sensitive safety strategies. This research addresses a critical gap by proposing a novel Conflict-Resilient Safety Management (CRSM) model, specifically designed for renewable energy infrastructure operating in conflict zones. The model integrates principles from the High Reliability Theory, Conflict Sensitivity, Resilience Engineering and Feedback Loops to offer a comprehensive framework for managing occupational risks in volatile environments.

Research Objectives and Questions. This article aims to investigate how occupational risks are identified, assessed, and managed in renewable energy projects operating in conflict-affected regions. The central research questions are: What are the primary occupational risks faced by workers in these projects? How do conflict dynamics influence the effectiveness of safety management systems? What strategies and frameworks can enhance worker safety in such volatile environments?

Summary of Contributions. Drawing on case studies from Iraq, South Sudan and Ukraine, as well as interviews and safety frameworks, this study presents key findings that highlight how occupational risks are amplified by weak governance, corruption and inadequate healthcare infrastructure. The Conflict-Resilient Safety Management (CRSM) model offers a structured, adaptive approach to mitigate these risks through decentralized decision-making, resilience planning and continuous learning. These insights are intended to be practically implemented in high-risk renewable energy projects. Building on the foundational concepts introduced in the previous section, the following chapter presents the theoretical underpinnings that guide this study.

II. Theoretical Framework

The complexity of occupational safety in conflict-affected renewable energy projects demands a multidisciplinary theoretical approach. This chapter introduces and synthesizes three key frameworks: High Reliability Theory, Conflict Sensitivity, and Resilience Engineering, to construct a conceptual model that addresses the unique challenges of managing occupational risk in volatile environments.

A. High Reliability Theory (HRT)

High Reliability Theory (HRT) explains how organizations operating in high-risk environments maintain safety through vigilance, decentralization, and continuous learning [7]. In conflict zones, renewable energy projects face unpredictable threats such as violence, infrastructure sabotage, and political instability. HRT principles, such as preoccupation with failure and deference to expertise, are essential for maintaining safety under such conditions.

In eastern Ukraine, a solar farm implemented decentralized decision-making and daily safety briefings. Site supervisors were empowered to halt operations during nearby shelling incidents, preventing injuries and equipment damage [7].

B. Conflict Sensitivity

Conflict sensitivity involves understanding how interventions interact with local conflict dynamics and adapting accordingly [8]. It ensures that safety planning accounts for social tensions, power imbalances, and potential triggers of violence. Example: In Kenya's Kakuma Refugee Camp, renewable energy projects were adapted to avoid exacerbating tensions between refugee and host communities. Hiring practices and energy distribution were modified to ensure equitable access, thereby reducing conflict [8].

C. Resilience Engineering

Resilience Engineering focuses on building systems that can adapt to disruption and continue functioning safely [9]. It emphasizes flexibility, redundancy, and learning loops-critical in conflict zones where conditions change rapidly. In South Sudan, a hybrid microgrid project used modular designs and trained local technicians to maintain operations during road blockades and political unrest. Redundant supply routes and flexible system configurations ensured continuity [10].

D. Conflict Sensitivity

Conflict sensitivity involves understanding how interventions interact with local conflict dynamics and adapting accordingly [8]. It ensures that safety planning accounts for social tensions, power imbalances, and potential triggers of violence. Example: In Kenya's Kakuma Refugee Camp, renewable energy projects were adapted to avoid exacerbating tensions between refugee and host communities. Hiring practices and energy distribution were modified to ensure equitable access to reduce conflict [8].

E. Feedback and Adaptation Loops

Feedback loops allow safety systems to evolve based on real-time data and worker input. This is vital in conflict zones, where static protocols may quickly become obsolete [11]. A wind project in Afghanistan used mobile apps for anonymous safety reporting. Weekly reviews led to changes in shift schedules and evacuation protocols based on recent conflict flare-ups [11].

F. Conceptual Model: Conflict-Resilient Safety Management

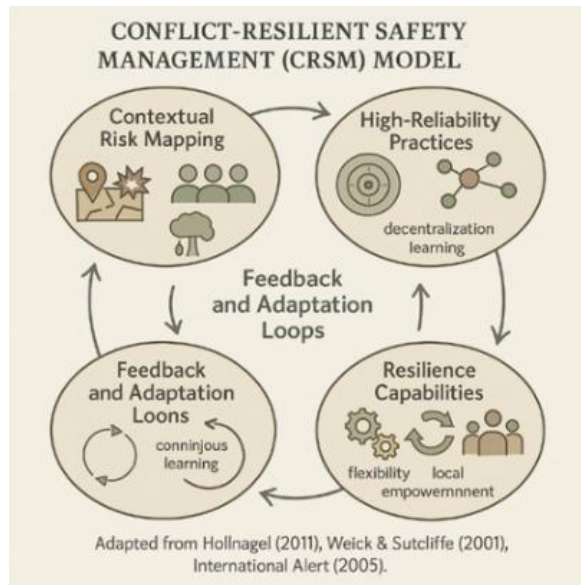


Fig. 1. Visual representation of the CRSM model

The CRSM model integrates the above theories into a unified framework for managing occupational safety in conflict-affected renewable energy projects. It includes:

- Contextual Risk Mapping - Identifies socio-political and environmental hazards
- High-Reliability Practices - Embeds vigilance and decentralized decision-making
- Resilience Capabilities - Builds adaptive capacity through flexible planning
- Feedback and Adaptation Loops - Enables continuous learning and system updates

III. Contextual Overview

This chapter provides a comparative overview of three conflict-affected countries – Iraq, South Sudan, and Ukraine – where renewable energy projects are being implemented amid political instability and security risks. It outlines the geopolitical context, renewable energy potential, and the key stakeholders involved in project development and safety governance.

A. Country Profiles and Energy Contexts

Iraq has experienced decades of conflict, including the U.S. invasion, sectarian violence, and the rise of ISIS. Although relatively more stable today, it remains vulnerable to regional tensions and internal unrest [12]. Iraq has set a target to generate 20% of its electricity from renewables by 2030. Despite high solar irradiance and wind potential, progress is slow, with only one major solar project launched as of 2025 [13]. Political interference, corruption, and dependence on Iranian gas hinder energy diversification [12].

South Sudan, since gaining independence in 2011, has been plagued by civil war, ethnic violence, and humanitarian crises. Security remains fragile [14]. With only 8.4% of the population having access to electricity, South Sudan has vast potential for off-grid solar and hybrid systems. Its lack of legacy infrastructure presents an opportunity to leapfrog into renewables. Infrastructure deficits, poverty, and climate-related shocks (e.g. floods) complicate energy deployment [15].

The ongoing war with Russia has devastated Ukraine's energy infrastructure. Over half of its electricity production capacity has been destroyed [14]. Ukraine has significant wind and solar potential, particularly in the southern regions. Prior to the war, it had one of the fastest-growing renewable sectors in Eastern Europe. Post-2022, reconstruction efforts have prioritized decentralized and resilient energy systems, including microgrids and hybrid renewables. Challenges: active conflict zones and military targeting of infrastructure, displacement of skilled labor and technical personnel, regulatory uncertainty and disrupted supply chains, psychological stress and trauma among energy workers.

The highlight of how each country has distinct but overlapping barriers in deploying renewable energy under conflict conditions is summarized in figure 2.

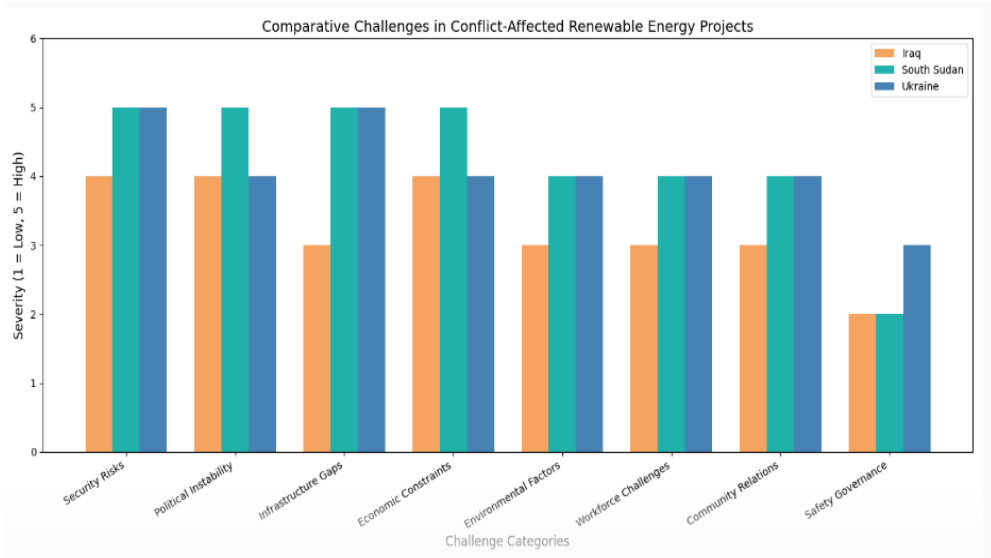


Fig. 2. Comparative challenges in Conflict-affected renewables Energy project

IV. Occupational risk and safety management in conflict - affected renewable energy projects

A, Types of occupational risks

Physical risks. Workers in conflict zones face direct physical threats such as: Landmines and unexploded ordnance (UXO) common in post-conflict areas like South Sudan and Afghanistan [16]; Armed attacks or sabotage, renewable infrastructure is often targeted due to its symbolic and strategic value; Poor infrastructure, inadequate roads and emergency services increase accident rates.

Table 1. Physical risk incidents in conflict zones

Country	Type of risk	Incident rate (per 100 workers / year)
Afghanistan	UXO related injuries	12.4
South Sudan	Armed attacks	8.7
Democratic Republic of Congo	Infrastructure failure	10.1

Psychological risks. Conflict environments exacerbate mental health challenges: Chronic stress and PTSD (post-traumatic stress disorder). Up to 30-70% of workers

in war zones report symptoms [17]; Isolation, Remote locations and security restrictions limit social interaction; Trauma exposure, witnessing violence or displacement events. Formula for psychosocial risk index (PRI):

$$PRI = \frac{(S+T+I)}{3} \quad (1)$$

Where:

S – Stress level (1 – 10)

T – Trauma exposure (1 – 10)

I – Isolation score (1 – 10)

Scores for stress (S), trauma exposure (T), and isolation (I) are derived from structured worker surveys. Each parameter is rated on a scale from 1 to 10, based on self-reported experiences and validated through interviews with field security and safety officers.

Operational risks. Operational disruptions are frequent due to: Supply chain breakdowns border closures, embargoes, or attacks on logistics [18]; Delays in construction due to security threats or lack of skilled labor; Communication failures, infrastructure damage affects coordination.

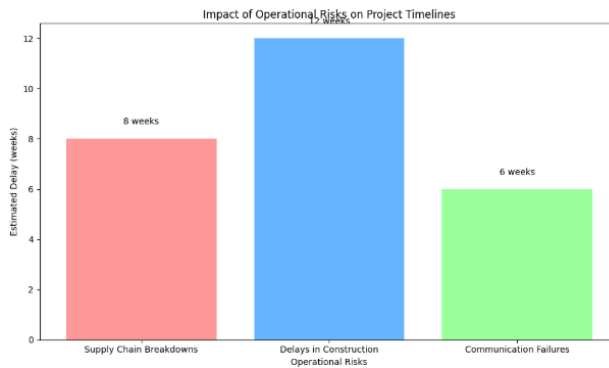


Fig. 3. Impact of operational risks on project timelines in conflict-affected renewable energy projects

Key insights. Delays in construction: have the highest estimated impact, causing up to 12 weeks of delay due to security threats and labor shortages. Supply chain breakdowns (e.g. border closures, attacks) can delay projects by around 8 weeks. Communication failures: due to infrastructure damage, may result in a 6-week delay.

Environmental risks. Environmental conditions in conflict zones often include:

Table 2. Environmental Stressors in Renewable Energy Sites

Location	Climate risk	Accessibility	Environmental degradation
North Mali	High	Low	High
Eastern Ukraine	Medium	Medium	Medium
Yemen Highlands	High	Very low	high

In conflict-affected renewable energy projects, occupational risks are not only shaped by direct threats but are significantly amplified by systematic weaknesses in governance, corruption, and healthcare infrastructure. These amplifiers exacerbate the severity and frequency of workplace hazards, reduce the effectiveness of mitigation strategies, and increase workers' vulnerability.

Weak Governance. Weak governance manifests in the inconsistent enforcement of safety regulations, fragmented oversight and limited institutional capacity to manage risks. In South Sudan, the absence of a coherent regulatory framework for labor and energy infrastructure has led to a near-total lack of enforcement of occupational standards. Many renewable energy projects operate in legal grey zones, relying on ad hoc agreements with local governments. In Iraq, overlapping jurisdictions between federal and regional governments create confusion over regulatory responsibilities, delaying inspections and enforcement. In Ukraine, while governance structures are more deployed, the ongoing war has diverted administrative capacity away from civilian infrastructure oversight, weakening the enforcement mechanism.

Corruption. Corruption undermines occupational safety by distorting procurement, inspection, and enforcement processes: Bribery in inspections allows contractors to bypass safety protocols, leading to substandard construction and unreported hazards [20]. Diversion of safety funds intended for PPE, training, or emergency response towards non-operational uses is common in both Iraq and South Sudan, where transparency mechanisms are weak [21]. In Ukraine, corruption risks have increased in areas under temporary occupation or near the front lines, where informal power structures influence project operations [20].

Table 3. Corruption Impact on safety compliance

Country	Bribery in inspection	Safety Fund Diversion	Compliance Score (0-10)
Iraq	High	High	4
South Sudan	Very High	Very High	3
Ukraine	Medium	Medium	6

Corruption Amplification Factor (CAF) can be determined:

$$CAF = B + D - C \quad (2)$$

Where:

B = Bribery Index

D = Diversion Index

C = compliance score.

Higher CAF indicates greater corruption impact. The Bribery Index (B) and Diversion Index (D) are qualitative assessments scored 1 to 10, based on expert interviews, NGO Reports, and transparency audits. The Compliance Score (C) is a numerical rating (0-10) derived from documented adherence to safety protocols, inspection records, and third-party evaluations.

Lack of Medical Facilities. The absence of adequate medical infrastructure in conflict zones significantly increases the fatality and morbidity rates of occupational incidents. In South Sudan, there are fewer than 0.15 physicians per 1000 people, and many rural project sites are over 100 km from the nearest clinic [22]. In Iraq, faces a shortage of trauma care facilities in areas affected by the past insurgencies, with many hospitals still under reconstruction [23]. In Ukraine, while urban centers have robust medical systems, frontline regions suffer from destroyed infrastructure and overwhelmed emergency services [22]. The below visualization supports that medical infrastructure deficiencies significantly amplify occupational risks in conflict-affected renewable energy projects. South Sudan's extreme response time (180 minutes) highlights the urgent need for mobile clinics and trauma-ready field units in remote project areas.

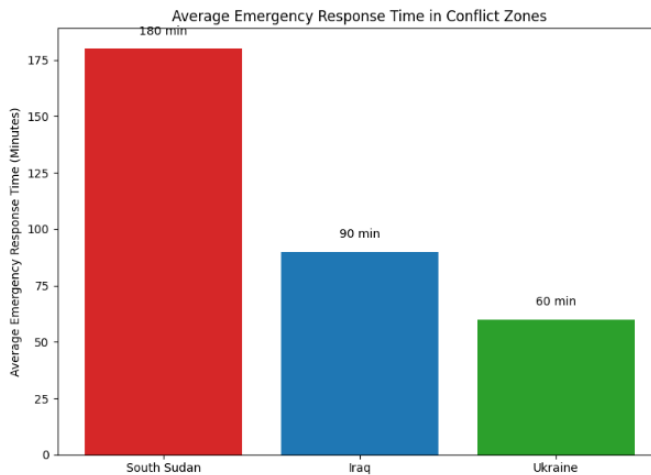


Fig. 4. Average Emergency response time in conflict zones, comparing South Sudan, Iraq and Ukraine.

In response to the risks identified, the following chapters explore current safety management strategies tailored to conflict zones.

V. Safety management strategies in conflict-affected renewable energy projects

In conflict-affected regions such as Iraq, South Sudan, and Ukraine, safety management in renewable energy projects requires a hybrid approach that blends conventional occupational safety practices with conflict-sensitive innovations. This chapter explores current practices, identifies persistent challenges, and highlights emerging innovations tailored to high-risk environments.

A. Current practices

Use of private security. In conflict-affected regions, private security firms are often indispensable to the operation of renewable energy projects. These firms fill the vacuum left by weak or absent state security forces and are tasked with protecting both personnel and infrastructure. Their roles typically include: Perimeter defense - Installation and monitoring of surveillance cameras, motion sensors, and physical barriers such as fencing and checkpoints. Escort services - Armed or unarmed escorts for engineers, technicians, and supply convoys travelling to and from remote or high-risk project sites. Threat intelligence - Gathering and analyzing local security data to anticipate risks such as insurgent activity, theft, or sabotage. In Iraq, solar energy projects in Anbar province have contracted local security firms with deep knowledge of tribal dynamics. These firms not only provide physical protection but also act as intermediaries with local communities, reducing the likelihood of attacks or sabotage [24]. While private security can enhance safety, it also introduces ethical and operational challenges, including: Accountability gaps in the event of misconduct; Escalation risks if security personnel are perceived as partisan; Cost burdens that can divert funds from core safety infrastructure.

Remote Monitoring and Automation. To reduce personnel exposure to physical and conflict-related hazards, renewable energy projects in conflict zones are increasingly adopting remote monitoring and automation technologies. These systems allow for real-time oversight and control of infrastructure with minimal on-site presence. Key technologies:

Drones - used for aerial inspections of wind turbines and solar panels, drones can detect structural damage, overheating or unauthorized access without requiring human inspectors to enter dangerous areas.

SCADA Systems (Supervisory Control and Data Acquisition): These centralized platforms allow operators to monitor and control energy production, detect faults, and adjust system parameters remotely. SCADA systems are particularly valuable in Ukraine, where frontline regions are inaccessible due to the ongoing conflict.

IoT Sensors: Internet of Things (IoT) devices are embedded in turbines, solar panels and substations to monitor: Structural integrity (e.g., vibration, tilt); Environmental conditions (e.g., temperature, wind speed); Energy output and efficiency. These sensors enable predictive maintenance, reducing downtime and preventing catastrophic failures. In Ukraine, wind farms near Mykolaiv have integrated IoT sensors with satellite uplinks to maintain operational visibility even during periods of shelling or power grid instability [25]. **Benefits:** Reduced personnel risk in high-threat areas; Faster response times to technical issues; Improved data accuracy for performance optimization. **Challenges:** Cybersecurity vulnerabilities: Remote systems are susceptible to hacking, especially in regions with active cyber warfare. Connectivity issues: In South Sudan and parts of Iraq, poor internet infrastructure can limit the effectiveness of real-time monitoring.

Emergency Evacuation Plans. In conflict-affected renewable energy projects, emergency evacuation planning is a critical component of occupational safety management. These plans are designed to ensure the rapid and safe withdrawal of personnel in the event of armed conflict, natural disaster, or technical failure. **Key Components of Evacuation Plans:**

- **Evacuation Routes and Rally Points** (Predefined escape routes are mapped and regularly updated based on evolving security conditions. Rally points are established at safe distances from project sites, often near UN or NGO compounds.)
- **Emergency Communication Systems** (Satellite phones, encrypted radios, and mobile apps are used to maintain communication during evacuations. In Ukraine, some wind farms have integrated Starlink terminals to ensure connectivity during blackouts or cyberattacks.)
- **Evacuation Drills and Training** (Regular drills are conducted to familiarize staff with procedures. Drills include simulations of armed attacks, landmine encounters, and medical emergencies.)

C. Challenges

Despite the implementation of safety strategies, renewable energy projects in conflict zones face persistent and systemic challenges that undermine occupational safety. These challenges are often interlinked with broader issues of governance, infrastructure, and social dynamics.

Limited Access to Training. Access to safety training is a foundational element of occupational risk management. However, in conflict-affected regions, training is often sporadic, underfunded, or entirely absent. South Sudan lacks formal institutions for technical and safety training in the renewable energy sector. Most workers are hired locally with minimal prior experience, and training is often delivered informally or on-the-job, if at all. In Iraq, logistical barriers such as road insecurity, curfews, and militia checkpoints hinder the delivery of training

programs to remote or high-risk areas. Trainers often require armed escorts, which increases costs and reduces frequency. Ukraine has seen many training centers in frontline regions damaged, repurposed for humanitarian use, or rendered inaccessible due to active conflict. Workers may be unaware of basic safety procedures, such as lockout/tagout protocols, PPE use, and emergency response procedures. This increases the likelihood of preventable accidents, especially during maintenance or installation phases. A 2023 incident in a solar installation in Jonglei State, South Sudan, resulted in two fatalities due to improper grounding of electrical equipment—an error linked to a lack of formal training. This root cause highlights a systematic gap in workforce competency and underscores the urgent need for standardized safety education in emerging solar markets to prevent avoidable fatalities.

Cultural and Language Barriers. Multinational teams are common in renewable energy projects, especially those funded by international donors or operated by foreign firms. However, while cultural and linguistic diversity enriches, it can also introduce safety risks. Language mismatches between expatriate engineers and local laborers can lead to miscommunication of safety instructions, especially during emergencies. Cultural norms may discourage workers from reporting hazards, questioning authority, or admitting a lack of understanding.

Inconsistent Enforcement of Safety Protocols. Even when safety protocols exist, their enforcement is often inconsistent due to fragmented governance, lack of oversight, or shifting control of territory. In Iraq, overlapping jurisdictions between federal, regional, and tribal authorities create confusion over who is responsible for enforcing labor and safety laws. This leads to patchy inspections and selective compliance. South Sudan suffers from a near-total absence of regulatory enforcement in rural areas. Safety standards are often determined by the implementing agency or contractor, with little external accountability. In Ukraine, enforcement varies significantly between government-controlled areas and contested zones. In some frontline regions, safety inspections are suspended entirely due to security concerns.

Innovations. In response to the complex safety challenges in conflict-affected renewable energy projects, a range of innovative strategies have emerged. These innovations aim to enhance worker protection, improve communication, and adapt safety practices to volatile and resource-constrained environments.

Mobile Safety Apps. Mobile applications are transforming how safety is managed in remote and high-risk project sites. These tools offer real-time, decentralized, and user-friendly platforms for safety communication and training. Key Features: Incident Reporting: Workers can instantly report hazards, injuries, or security threats. Geofenced Alerts, apps can trigger location-based warnings (e.g., proximity to conflict zones or minefields). Digital Training Modules, interactive safety training can be accessed on demand, even in low-bandwidth environments. Offline

Functionality, crucial in areas with unreliable internet, such as rural South Sudan or frontline zones in Ukraine.

Community-Based Safety Liaisons. In fragile contexts, community engagement is not just a social responsibility, it is a safety imperative. Community-based safety liaisons serve as trusted intermediaries between project teams and local populations. Early Warning Systems provide real-time intelligence on local conflict dynamics, environmental hazards, or community tensions. Cultural Mediation helps adapt safety protocols to local customs and languages, improving compliance and trust. Dispute Resolution can de-escalate conflicts between workers and residents, especially over land use or access.

Conflict-Sensitive Safety Training. Traditional safety training often fails in conflict zones because it overlooks the social, political, and psychological realities of the environment. Conflict-sensitive training addresses this gap by integrating contextual awareness into safety education. Core Modules could contain: Conflict Awareness (understanding local power dynamics, armed group behavior, and conflict triggers); De-escalation Techniques (nonviolent communication, negotiation, and situational judgment); Trauma-Informed First Aid (psychological first aid and care for blast or gunshot injuries). Delivery Methods:

- Blended Learning: Combining in-person workshops with mobile-based modules.
- Peer-to-Peer Training: Empowering local workers to train others in their language and cultural context.
- Scenario-Based Drills: Simulations of conflict-related emergencies (e.g., evacuation under fire, checkpoint navigation).

VI. Conclusion

Occupational safety in conflict-affected renewable energy projects demands a paradigm shift from conventional models to adaptive, context-sensitive frameworks. Through the lens of Iraq, South Sudan, and Ukraine, this study has shown that safety risks are shaped not only by direct threats, such as violence, landmines, and infrastructure failure, but also by systemic amplifiers like weak governance, corruption, and inadequate healthcare.

To address these challenges, the Conflict-Resilient Safety Management (CRSM) model integrates High Reliability Theory, Conflict Sensitivity, Resilience Engineering, and Feedback Loops into a unified approach. This model emphasizes vigilance, decentralization, adaptability, and continuous learning, principles essential for operating safely in volatile environments. The analysis of current practices and innovations, ranging from private security and remote monitoring to mobile safety apps and community-based liaisons, demonstrates that effective safety management must be both locally grounded and technologically enabled. Ultimately, ensuring worker protection in conflict zones is not only a technical

challenge but a socio-political imperative, requiring collaboration, flexibility, and a deep understanding of the local context.

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APPENDIX A: VISUAL AIDS AND DATA APPENDICES

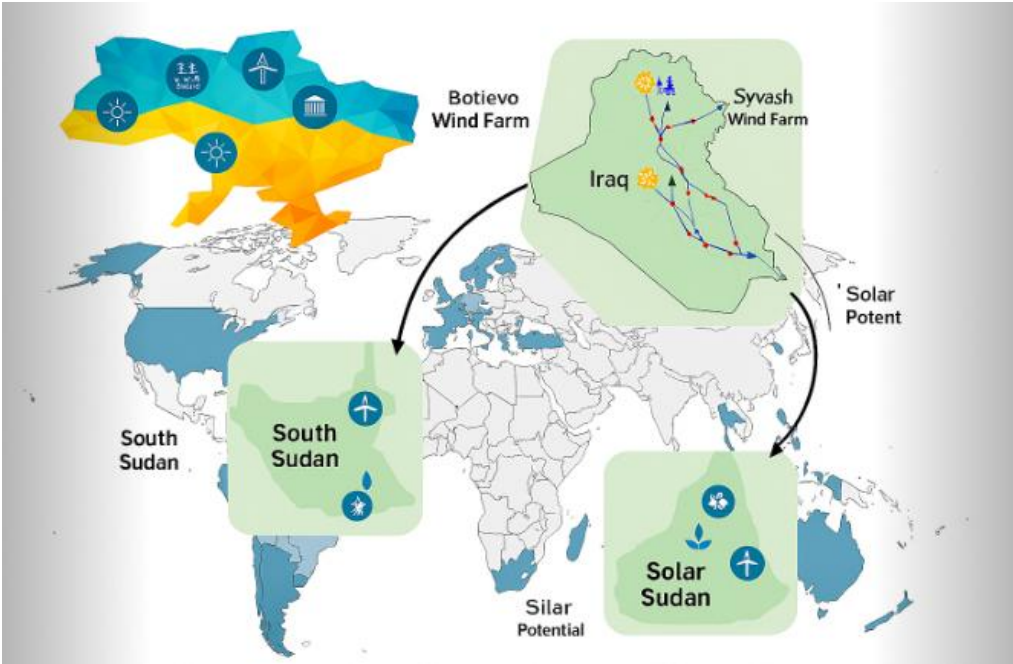


Fig. A1. Map of Renewables in Iraq, South Sudan, and Ukraine

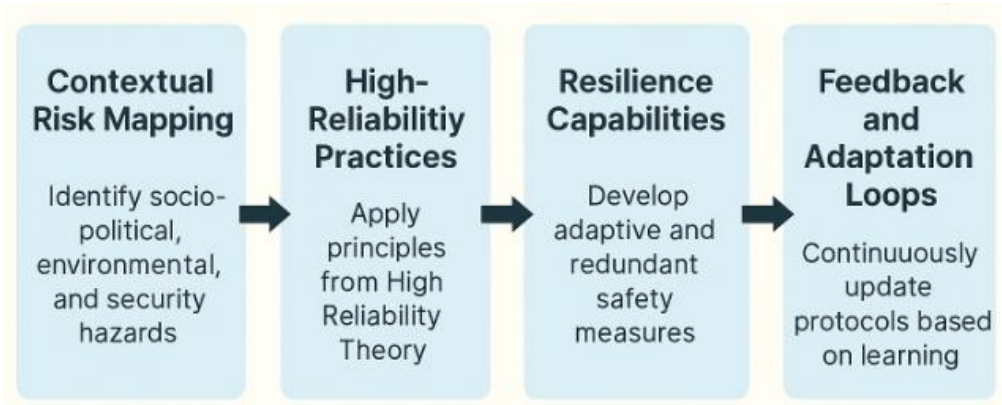


Fig. A2. Infographic: Conflict-Resilient Safety Management (CRSM) Model Overview

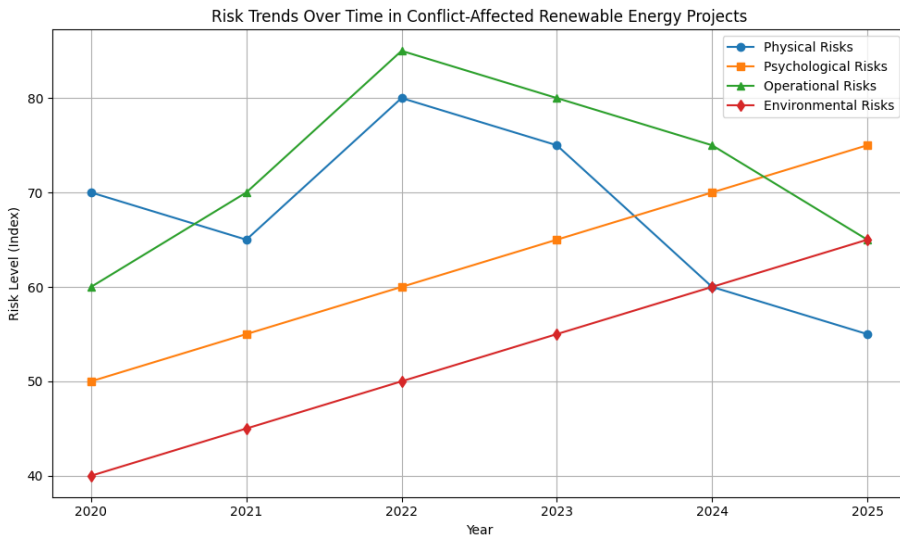


Fig. A3. Chart: Risk Trends Over Time in Conflict-Affected Renewable Energy Projects

Physical Risks peaked in 2022 (80) but declined steadily to 55 by 2025, likely due to improved security measures and remote monitoring.

Psychological Risks show a continuous upward trend, reaching 75 in 2025, reflecting cumulative stress and trauma exposure.

Operational Risks spiked in 2022 (85) during major conflict escalations, then decreased as resilience strategies were implemented.

Environmental Risks steadily increased from 40 to 65, indicating growing climate-related stressors and accessibility issues.

APPENDIX B: INTERVIEW METHODOLOGY

1. Description of Interview Methodology

Sampling Strategy:

A purposive sampling approach was used to identify participants with direct experience in renewable energy projects located in conflict-affected regions. Selection criteria included:

- Minimum of 1 year of field experience in Iraq, South Sudan, or Ukraine.
- Roles in safety management, engineering, logistics, or community liaison.
- Representation from both international and local stakeholders.

Interview Format:

Interviews were semi-structured, allowing flexibility to explore emergent themes while maintaining consistency across core questions. Each session lasted between 45 and 60 minutes and was conducted via secure video conferencing platforms due to security and accessibility constraints.

Ethical Considerations:

- Informed consent was obtained from all participants.
- Anonymity and confidentiality were guaranteed.
- Sensitive topics (e.g., trauma, corruption) were approached with care, and participants could skip questions.
- Ethical approval was granted by the doctoral ethics committee of the National University of Science and Technology POLITEHNICA Bucharest.

2. Sample Interview Questions

1. What are the most frequent safety risks you encounter in your current project?
2. How does the local conflict environment affect your ability to implement safety protocols?
3. Can you describe a situation where safety procedures had to be adapted due to conflict dynamics?
4. What role do local communities play in shaping safety outcomes?
5. How do you manage psychological stress among workers in high-risk zones?
6. What kind of training or support do workers receive regarding emergency evacuation?
7. Have you observed any corruption-related challenges in safety enforcement?
8. What technologies or innovations have helped improve safety in your project?
9. How do you communicate safety instructions across language or cultural barriers?
10. What improvements would you recommend for future safety management in conflict zones?

3. Participant Demographics

Table 1

Role	Gender	Country of Origin
Safety Manager	Male	Iraq
Field Engineer	Female	Ukraine
Logistics Coordinator	Male	South Sudan
Community Liaison	Female	South Sudan
NGO Safety Advisor	Male	Denmark

Renewable Energy Consultant	Female	Romania
Site Supervisor	Male	Ukraine
Trauma Care Nurse	Female	Iraq

4. Summary of Qualitative Findings

- Decentralized Decision-Making: Empowering local supervisors to halt operations during conflict events was cited as a critical safety measure.
- Psychological Stress: PTSD and chronic stress were prevalent, especially among local workers. Mobile apps and peer support networks were helpful.
- Corruption and Governance Gaps: Safety compliance was often undermined by bribery and diversion of funds, particularly in Iraq and South Sudan.
- Community Engagement: Projects that employed community liaisons reported fewer incidents and better local cooperation.
- Training Deficits: Lack of formal safety training was a recurring issue, especially in South Sudan. Peer-to-peer and mobile-based training were seen as promising alternatives.
- Technology Use: IoT sensors, drones, and SCADA systems were praised for reducing physical exposure and improving monitoring.
- Evacuation Planning: Regular drills and satellite communication were essential, but infrastructure damage and access restrictions remained major barriers.

APPENDIX C: CRSM MODEL TOOLKIT

1. Step-by-Step Implementation Guide

This guide outlines the four key steps for implementing the CRSM model in conflict-affected renewable energy projects.

Step 1: Contextual Risk Mapping

- Conduct socio-political and security risk assessments.
- Use GIS mapping and conflict analysis frameworks.

Step 2: High-Reliability Practices

- Establish decentralized decision-making protocols.
- Conduct daily safety briefings and empower 'stop-work authority'.

Step 3: Build Resilience Capabilities

- Design redundancy in supply chains and energy systems.
- Prepare mobile medical units and backup communication systems.

Step 4: Feedback and Adaptation Loops

- Deploy mobile apps for incident reporting.
- Schedule weekly risk review meetings.

2. Practitioner Checklist

- ☐ Risk map completed and updated weekly.
- ☐ Local security liaison appointed.
- ☐ Emergency evacuation plan tested.
- ☐ Mobile safety reporting system active.
- ☐ Redundant supply routes identified.

3. Monitoring & Evaluation Template

Indicator	Traget	Frequency
% of staff trained in CRSM	100%	Quarterly
# of safety incidents	<2	Monthly
Average. evacuation time (min)	<45	Quarterly

APPENDIX D: SAMPLE CALCULATIONS AND RAW DATA

Sample Calculation for Psychosocial Risk Index (PRI): Using hypothetical values for S, T, and I.

Formula: $PRI = \frac{(S+T+I)}{3}$

Where:

S= Stress level (1–10)

T = Trauma exposure (1–10)

I = Isolation score (1–10)

Example:

S = 8, T = 7, I = 6

$PRI = \frac{(S+T+I)}{3} = 7$

Sample Calculation for Corruption Amplification Factor (CAF): Using example values for B, D, and C.

Formula: $CAF = B + D - C$

Where:

B = Bribery Index (1–10)

D = Diversion Index (1–10)

C = Compliance Score (0–10)

Example:

B = 7, D = 6, C = 4

$CAF = 7 + 6 - 4 = 9$

Raw Data Tables: Placeholder for structured data used in risk analysis.

Table 2

Psychosocial Risk Survey Results

Participant ID	Stress (S)	Trauma (T)	Isolation (I)
P001	8	7	6
P002	6	5	7
P003	9	8	8
P004	5	4	6

Table 3

Corruption Risk Assessment

Region	Bribery Index (B)	Diversion Index (D)	Compliance Score (C)
Iraq	7	6	4
South Sudan	8	7	3
Ukraine	5	4	6

Sensitivity Analysis: Description of how changes in input parameters affect PRI and CAF outcomes.

Psychosocial Risk Index (PRI) is sensitive to increases in any of the three parameters.

For example:

If Stress increases from 6 to 9 while Trauma and Isolation remain constant at 7:

$$PRI = \frac{(9+7+7)}{3} = 7.67$$

Corruption Amplification Factor (CAF) is most sensitive to reductions in

Compliance Score (C). For example:

If Compliance drops from 6 to 3 while Bribery and Diversion remain at 7 and 6:

$$\text{CAF} = 7 + 6 - 3 = 10$$

APPENDIX E: SAMPLE CALCULATIONS AND RAW DATA

Iraq – Conflict Sensitivity & Governance Challenges

Security firms with tribal knowledge acted as intermediaries, reducing sabotage risks and improving local trust. Overlapping jurisdictions and bribery in inspections undermined safety compliance, highlighting the need for CRSM's feedback and adaptation mechanisms. In Iraq, the integration of local security actors and adaptive safety planning illustrates how CRSM can navigate fragmented governance and corruption. These measures improved operational safety despite systemic challenges.

South Sudan – Resilience Engineering & Community Engagement

Modular microgrid designs and local technician training allowed operations to continue during road blockades and unrest. Community-based safety liaisons helped mediate tensions and adapt safety protocols to local customs. South Sudan's reliance on modular infrastructure and community liaisons reflects the CRSM model's resilience and conflict-sensitive dimensions. These strategies ensured continuity and reduced friction with local populations.

Ukraine – High Reliability & Feedback Loops

Ukraine's energy infrastructure has been heavily targeted during the war, making contextual risk mapping essential. Wind farms near Mykolaiv empowered site supervisors to halt operations during shelling, demonstrating decentralized decision-making and preoccupation with failure—key High Reliability Theory principles. Mobile apps allowed anonymous safety reporting, leading to real-time adjustments in evacuation protocols and shift schedules. These practices exemplify the CRSM model's emphasis on adaptive safety, enabling rapid response to evolve threats and minimizing worker exposure.

ENTREPRENEURSHIP AND COLLABORATIVE INNOVATION IN MEDICAL DEVICES: SMALL AND MEDIUM-SIZED ENTERPRISE COMPETITIVENESS UNDER THE EUROPEAN MEDICAL DEVICE REGULATION

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Abstract

This paper explores how entrepreneurship and collaborative innovation enhance the competitiveness of small and medium-sized enterprises (SMEs) in the European medical device sector under the Medical Device Regulation (MDR 2017/745). It examines the strategic role of multi-stakeholder partnerships (spanning academia, industry, clinicians, and regulators) in navigating regulatory complexities and accelerating innovation. The study highlights how SMEs leverage collaborative ecosystems to meet compliance, improve product quality, and access new markets. Findings suggest that adaptive innovation models and regulatory alignment are critical for sustaining SME growth and competitiveness in a rapidly evolving healthcare landscape.

Keywords

Medical Device Regulation (EU 2017/745); entrepreneurship; collaborative innovation; small and medium-sized enterprises (SMEs); competitiveness; digital twin technology; regulatory compliance; healthcare innovation

I. Introduction

The medical device industry is one of the European Union (EU)'s most dynamic and innovation-driven sectors. Advances in digital health, artificial intelligence (AI), and smart monitoring systems are transforming patient care and creating new opportunities for sustainable healthcare solutions. However, this innovation

landscape has been profoundly reshaped by the implementation of the Medical Device Regulation (EU 2017/745) (MDR), which came into force in May 2021. Designed to enhance safety, traceability, and clinical effectiveness, MDR establishes a stricter regulatory environment that demands greater evidence, robust post-market surveillance, and transparent compliance mechanisms across all types of devices.

While the regulation aims to strengthen the internal market and patient trust, its implementation has raised concerns about the competitiveness of European firms, especially small and medium-sized enterprises (SMEs). SMEs are widely recognized as the primary drivers of disruptive innovation, yet they often face disproportionate burdens under MDR due to limited financial resources, staff expertise, and access to notified bodies (an independent, EU-designated organization accredited to evaluate whether medical devices meet the regulatory, safety, and performance requirements). This dynamic creates a paradox: the very firms most capable of advancing breakthrough technologies may be those most at risk of being slowed down or excluded from the market. At the same time, MDR can also function as a catalyst by setting higher quality benchmarks, enhancing international credibility, and creating incentives for sustainable design. This dual impact, short-term challenges but potential long-term opportunities, frames the central question of how SMEs can adapt and thrive under the new regulatory regime.

In this context, entrepreneurship and collaborative innovation emerge as crucial strategies. Entrepreneurial agility allows SMEs to adapt business models, explore alternative financing mechanisms, and align sustainability with competitiveness. Collaboration (with hospitals, universities, clusters, and European research programs such as Horizon Europe) enables resource-sharing, accelerates regulatory learning, and provides access to essential clinical data. Together, these strategies represent pathways for SMEs to mitigate MDR's short-term burdens while exploiting its long-term opportunities.

In this paper, entrepreneurship refers to the capacity of SMEs to mobilize resources, design business models, and take calculated risks to bring medical technologies from concept to market under the demanding requirements of MDR (EU 2017/745). Collaborative innovation denotes the joint creation of knowledge, processes, and solutions through partnerships among SMEs, hospitals, research centres, investors, and regulatory actors, enabling smaller firms to access clinical data, share compliance costs, and accelerate evidence generation. Together with these two dimensions, smart and sustainable development is understood as the integration of data-driven, connected, and AI-enabled device capabilities with eco-design and resource-efficient practices across the device life cycle, from design and manufacturing to use and end-of-life.

To ground this analysis, the paper uses the case study of Ventijet Health Technology. The medical devices developed by Ventijet integrate digital twin

technology (a virtual replica of a medical device or patient system that enables real-time monitoring, simulation, and predictive decision-making) and advanced monitoring to optimize ventilation therapies in intensive care units, exemplifying how SMEs pursue both technological excellence and sustainable development in a highly regulated context. To investigate how SMEs can sustain competitiveness under MDR (EU 2017/745), we employ a qualitative case study of Ventijet Health Technology, combining documentary evidence, policy analysis, and industry sources.

The remainder of the paper is organized as follows. Section II reviews literature on entrepreneurship, smart and sustainable development, collaborative innovation, and EU 2017/745. Section III outlines the methodology. Section IV presents the Ventijet analysis. Section V discusses MDR's impact on competitiveness through our tripartite framework. Section VI develops policy and managerial implications. Section VII concludes with contributions, limitations, and avenues for future research.

The central research question of this paper is therefore: How does MDR (EU 2017/745) affect the competitiveness of SMEs in the medical device industry, and in what ways can entrepreneurship and collaborative innovation support smart and sustainable development under these conditions? By combining a review of the literature with in-depth research, this work contributes to understanding the interplay between regulation, innovation, and competitiveness in one of Europe's most strategically important industries.

II. Literature review

A. Entrepreneurship and innovation in medical devices

Entrepreneurship plays a pivotal role in the medical device industry, as startups and small ventures are often the source of disruptive innovation (innovations that create new markets or value networks, often displacing established products or practices). Unlike large corporate manufacturers, which tend to prioritize risk minimization and incremental improvement, startups are better positioned to explore radical technologies (high-impact technologies that fundamentally alter existing medical device paradigms, introducing entirely new capabilities) such as AI-driven monitoring systems, connected devices, or digital twin applications [1,2]. The entrepreneurial capacity to quickly prototype, test, and adapt products allows smaller companies to identify unmet clinical needs and translate them into novel solutions with greater speed than established incumbents.

However, entrepreneurship in medical devices faces substantial barriers due to the regulatory intensity of the sector. Unlike in digital or consumer technologies, where "trial and error" innovation is feasible, medical devices demand rigorous

safety validation and regulatory approval before commercialization [3]. This tension means that startups often rely on collaborative innovation networks, including partnerships with hospitals, universities, and accelerators, to bridge gaps in resources, expertise, and compliance knowledge [4].

Corporate firms, by contrast, maintain a focus on incremental innovation (step-by-step improvements to existing devices, enhancing performance or usability without changing the core concept) and product line extensions, seeking to safeguard established market shares. Evidence from ventilator and monitoring device markets demonstrates that major corporations such as Dräger, Philips, or Getinge invest heavily in process optimization and incremental improvements, while more disruptive developments, such as AI-powered ventilation support, tend to emerge from SMEs and startups [5]. This dual innovation dynamic underscores the importance of entrepreneurship as the driver of technological renewal in the medical device sector.

B. Smart and sustainable development in healthcare

In recent years, the medical device industry has increasingly integrated the principles of smart technology and sustainability into innovation strategies. Smart devices, including predictive monitoring systems, AI-enabled decision support tools, and cloud-based analytics platforms, enhance clinical outcomes by providing real-time data insights, improving diagnostic precision, and supporting tailored patient management [6]. The introduction of digital twins (virtual models of a patient's physiology) illustrates this shift toward individualized, data-driven care [7].

Alongside smart functionality, sustainability has become a critical dimension of competitiveness. Medical devices contribute significantly to healthcare's environmental footprint, prompting increased attention to eco-friendly materials, energy-efficient manufacturing processes, and circular economy principles such as reuse, refurbishment, and recycling [8]. The European Green Deal and the EU's Circular Economy Action Plan reinforce these expectations, creating pressure on device manufacturers to align with environmental, social, and governance (ESG) objectives [9].

Startups and SMEs are particularly well-placed to lead this transition. Their flexible structures enable the integration of sustainable design early in product development, while digital technologies, such as Internet of Things (IoT), enable monitoring or cloud-based data analysis, improving both patient outcomes and system-level resource efficiency [10]. Smart and sustainable development is therefore not only a response to societal and policy pressures but also a potential source of competitive advantage in an increasingly demanding regulatory and market environment.

C. Collaborative innovation

The complexity of medical device development makes collaborative innovation essential. Collaborative innovation refers to the process by which firms, hospitals, universities, and public agencies share knowledge, infrastructure, and resources to accelerate product development and reduce costs [11]. This is especially critical in the context of MDR, where generating robust clinical evidence and building regulatory-compliant systems often exceeds the capacity of individual SMEs.

Clusters and consortia play a central role in facilitating collaboration. For example, the Basque Health Cluster in Spain provides a platform for SMEs, startups, hospitals, and universities to share expertise and build synergies in health technologies. At the European level, Horizon Europe programs and European Institute of Innovation and Technology (EIT Health) initiatives foster cross-border collaborations, supporting joint R&D, access to funding, and regulatory learning. Such networks lower the barriers to entry for SMEs and accelerate the adoption of disruptive technologies in clinical environments [12].

Hospital-industry partnerships represent another vital form of collaborative innovation. By involving clinicians early in the design and testing of devices, companies gain access to real-world data, user feedback, and clinical validation pathways that are otherwise difficult to obtain. These partnerships not only improve product-market fit but also generate the clinical evidence necessary for MDR compliance. In this sense, collaborative innovation is both a practical necessity and a strategic asset for SMEs seeking to remain competitive under the new regulatory paradigm.

D. MDR (EU 2017/745): Overview and implications

The MDR (EU 2017/745) introduced one of the most significant regulatory overhauls in the European health technology sector in decades. Its key features include:

- Stricter classification rules covering software, digital health, and connected devices;
- Enhanced clinical evaluation requirements, mandating robust evidence and post-market surveillance;
- CE marking (the certification mark indicating that a medical device complies with MDR safety, performance, and regulatory requirements) requirements tied to comprehensive conformity assessments;
- Greater transparency through the EUDAMED (the European Database on Medical Devices, designed to centralize information on device registration, clinical investigations, and vigilance) database and Unique Device Identification (UDI), which is a standardized system for uniquely identifying medical devices, improving traceability and post-market safety.

The benefits of MDR are clear: improved patient safety, harmonized standards across member states, and increased trust in European-made devices [13]. However, MDR also creates substantial challenges: certification timelines have lengthened, costs have escalated, and the number of designated notified bodies has decreased, creating bottlenecks [14]. These issues disproportionately affect SMEs, which face difficulty securing regulatory expertise, financing clinical trials, and absorbing the delays in time-to-market [15]. Thus, MDR is a double-edged sword: while it strengthens Europe's reputation for quality and safety, it simultaneously risks undermining SME competitiveness if adaptation mechanisms are not adequately supported.

E. Competitiveness and SMEs

Literature consistently highlights SMEs as the most vulnerable actors under MDR. Studies show that smaller firms often experience reduced innovation speed, delayed product launches, and financing pressures linked to the regulatory changes [16]. In particular, the requirements for continuous post-market surveillance and the generation of clinical evidence impose an especially heavy burden. Unlike large corporations, which benefit from established regulatory departments, extensive networks, and experienced multidisciplinary teams, SMEs typically lack the internal structure, expertise, and resources to sustain these obligations. This asymmetry can result in strategic setbacks for smaller firms, including product withdrawals or complete market exits [17].

Nevertheless, research also points to strategic pathways by which SMEs can remain competitive. Collaborative approaches (such as joint ventures with hospitals, participation in EU-funded projects, or partnerships within health clusters) allow smaller firms to pool resources and knowledge [12]. SMEs that integrate sustainability and smart technologies into their designs may also differentiate themselves competitively, appealing to hospitals and regulators prioritizing safety, efficiency, and environmental impact [10].

In this sense, MDR does not solely represent a barrier; it also provides an opportunity for SMEs to professionalize operations, align with sustainability goals, and strengthen international competitiveness. The illustration of Ventijet Health Technology, analysed in this paper, exemplifies how entrepreneurial ventures can leverage innovation and collaboration to overcome regulatory challenges and sustain competitiveness in a highly regulated sector.

III. Methodology

A. Research approach

This study adopts a qualitative case study methodology, which is particularly suited to exploring complex, context-dependent phenomena such as the impact of regulatory frameworks on innovation and competitiveness. The case study method allows for in-depth analysis of both organizational processes and external environmental pressures, offering insights into how SMEs adapt their strategies in response to the MDR (EU 2017/745).

A case study also enables the integration of multiple data sources (documentary evidence, policy frameworks, and market intelligence) into a coherent analysis [18]. The research examined entrepreneurship and innovation in smart and sustainable medical devices. The present study deepens the investigation into how entrepreneurial and collaborative strategies can mitigate the regulatory challenges faced by SMEs in the European medical device sector.

B. Case selection rationale

The selected example, Ventijet Health Technology and its medical device portfolio, represents a paradigmatic example of SME-led innovation under MDR constraints. Ventijet is a small, innovation-driven company specializing in respiratory care devices, whose flagship product leverages digital twin technology and advanced monitoring to optimize ventilation therapies in intensive care units.

This model was chosen for three reasons:

- SME context – Ventijet Health Technology reflects the characteristics of many European SMEs in the medical device industry: highly innovative, resource-constrained, and disproportionately affected by MDR's requirements;
- Technological novelty – The product portfolio exemplifies the integration of smart technologies (AI, predictive modeling, and real-time monitoring) and sustainability goals, both of which are increasingly relevant in the industry;
- Regulatory relevance – As a product portfolio covering different medical devices of varying risk levels, scopes, and intended uses under MDR, the medical devices must undergo rigorous conformity assessment, clinical evaluation, and certification procedures. This makes it a strong example to examine how SMEs navigate MDR's hurdles while striving for competitiveness.

C. Data sources

To ensure triangulation and validity, the analysis draws from a combination of primary and secondary sources:

- Thesis data: Project documentation, technical specifications of the medical device portfolio, and prior analyses of Ventijet Health Technology's business and regulatory strategy;
- Regulatory documents: MDR (EU 2017/745), Medical Device Coordination Group (MDCG) guidance, and European Commission policy papers;
- Market reports: Industry analysis on the medical device sector, focusing on smart and sustainable innovations, investment trends, and MDR's market impact (e.g., MedTech Europe reports, Frost & Sullivan);
- Academic literature: Peer-reviewed studies on entrepreneurship, collaborative innovation, and regulatory adaptation in medical devices;
- Policy papers: EU Horizon Europe program documents, position papers from MedTech Europe, and open letters to the European Commission concerning SME challenges under MDR;

This mixed evidence base provides a comprehensive understanding of the demonstration, capturing both firm-level dynamics and system-level regulatory pressures.

D. Analytical framework

The competitiveness of SMEs under MDR is analysed through a framework structured around three key axes:

1. Innovation Capacity (Technological and Business Model Innovation):

- Examine the extent to which SMEs like Ventijet Health Technology can develop and integrate smart and sustainable technologies (e.g., digital twin, predictive monitoring).
- Considers business model innovations such as subscription-based services, equipment leasing, and partnerships with healthcare providers;

2. Regulatory Adaptation (Compliance with MDR):

- Analyzes the strategies employed to meet MDR's stringent requirements: clinical evidence generation, notified body interactions, CE marking, and post-market surveillance;
- Evaluates the balance between regulatory burden (time, cost, expertise) and competitive advantage (trust, safety, international market access);

3. Entrepreneurial Strategies (Collaboration, Investment, Sustainability):

- Investigates how SMEs leverage entrepreneurial practices to overcome resource constraints;
- Focuses on collaboration with hospitals, clusters, and EU research programs to share knowledge and resources;
- Reviews investment strategies, including venture capital, industrial partnerships, and public funding, as well as the integration of sustainability practices as differentiators in competitive positioning.

This tripartite framework enables a structured assessment of how SMEs can sustain competitiveness by linking entrepreneurial agility, collaborative innovation, and regulatory adaptation within the evolving European medical device landscape.

IV. Case study: Ventijet Health Technology

A. Background

Ventijet Health Technology is a European SME founded in 2020 and dedicated to the design and development of medical devices for respiratory care. With a lean team of around ten core members (bringing together expertise in intensive care medicine, biomedical and industrial engineering, and regulatory affairs) Ventijet reinforces its capabilities through specialist advisors and strategic partnerships with hospitals, research groups, and industrial collaborators. Planned new hires in software, artificial intelligence, and business development further strengthen its multidisciplinary profile.

Founded with the mission of advancing intensive care and monitoring technologies, Ventijet exemplifies how entrepreneurial firms can drive innovation in highly regulated environments. Its projects represent a breakthrough in critical care by enabling predictive and personalized ventilation management through digital twin technology and advanced data analytics. Conceived to address the pressing clinical challenge of improving patient outcomes in mechanical ventilation while reducing ventilator-induced complications, the systems combine real-time monitoring with predictive modelling to deliver actionable insights to clinicians, thereby enhancing evidence-based decision-making in Intensive Care Units (ICUs).

The regulatory roadmap for Ventijet's products follows MDR (EU 2017/745) pathways applicable to advanced ventilators and software-driven monitoring devices. Key milestones include (Fig. 1):

- (i) Design and risk management under ISO 13485 (the international standard for quality management systems specific to medical devices, required under MDR (EU 2017/745)) Quality Management System (QMS) (an organizational framework of processes and procedures ensuring compliance, safety, and continuous improvement in device development and commercialization);

- (ii) Usability testing and pre-clinical bench validation;

- (iii) Ongoing clinical trials at hospitals, with early results indicating up to 25% improvement in oxygenation and lung recruitment in acute respiratory distress syndrome (ARDS) patients;

- (iv) Preparation of clinical evaluation reports and notified body engagement for CE marking, targeted for 2027–2028;

- (v) implementation of post-market surveillance (PMS) and periodic safety update reports (PSUR) after market entry.

Ventijet faces concrete challenges typical of SMEs under MDR: limited access to notified bodies, high costs of generating compliant clinical evidence, reliance on public funding mechanisms, and the need to align hospital collaborations with regulatory timelines. These hurdles, while significant, have also driven the company toward greater professionalization, cross-border partnerships, and the integration of sustainability and AI-driven design as strategic differentiators. This positioning makes Ventijet a paradigmatic case for exploring how SMEs navigate the dual challenges of competitiveness and MDR compliance.

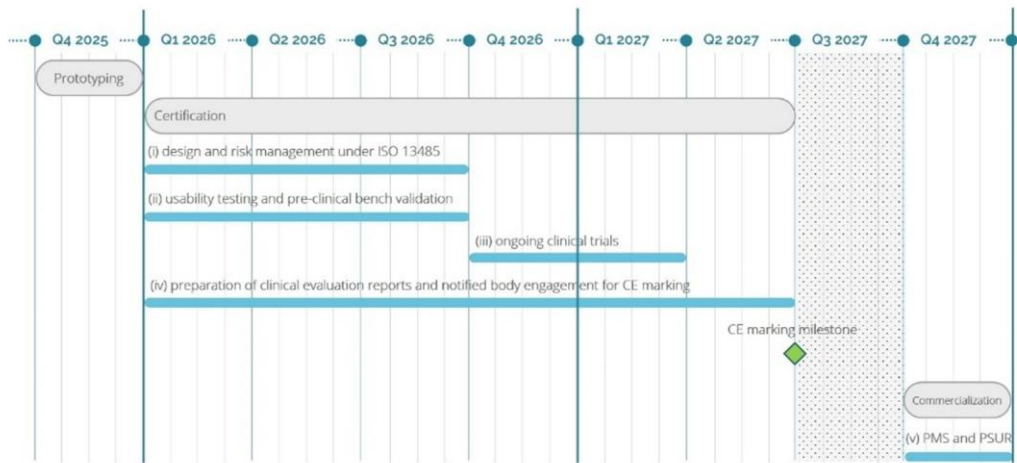


Fig. 2. Ventijet's regulatory product certification roadmap example

B. Technological innovation

At the core of the products is their digital twin model of the patient's lungs, which allows for continuous simulation of respiratory mechanics. This enables: (a) real-time adaptation of ventilation strategies to patient-specific needs; (b) early detection of complex respiratory patterns, such as asynchronous breathing or abnormal pressure dynamics; (c) monitoring multiple parameters, extending beyond the capabilities of conventional ventilators.

This technological innovation aligns with the broader trend of smart healthcare systems, where artificial intelligence, predictive analytics, and IoT-enabled devices converge to enhance clinical practice. Importantly, the product portfolio not only improves patient safety but also contributes to resource efficiency, as more precise monitoring reduces unnecessary interventions and supports sustainability in critical care.

C. Business model innovation

Ventijet's innovation extends beyond technology into its business model strategy. Recognizing that hospitals often face budget constraints and risk aversion toward novel technologies, the company developed flexible access models:

- Subscription-based services, allowing hospitals to access patients' data analytics and cloud monitoring without prohibitive upfront costs;
- Leasing models for equipment, lowering financial barriers to adoption;
- Collaborative partnerships with healthcare institutions, enabling early validation, co-development, and shared learning on product deployment.

These entrepreneurial strategies not only mitigate financial constraints but also facilitate faster market penetration by aligning with hospitals' procurement realities. They also reflect a broader shift in the medical device industry toward servitization, where value is increasingly tied to ongoing services and data-driven insights rather than one-off equipment sales.

D. Regulatory roadmap MDR (EU 2017/745)

Under the MDR (EU 2017/745), medical devices are classified into four categories according to the level of risk they pose to patients and users: Class I (low risk, e.g. non-invasive instruments), Class IIa (moderate risk, e.g. dental fillings, infusion pumps), Class IIb (higher risk, e.g. anaesthesia machines, long-term invasive devices), and Class III (highest risk, e.g. implantable defibrillators, ventilators, cardiovascular stents). The regulatory pathway is progressively more demanding as the device class increases. While Class I devices may follow a self-certification route, Classes IIa, IIb, and III require formal conformity assessment by a notified body. This tiered structure means that the regulatory effort, cost, and timelines are substantially different depending on the class of device a company seeks to commercialize. For SMEs, targeting higher-risk classes typically entails a disproportionately high compliance burden compared to larger corporations with dedicated regulatory infrastructures.

Products in the portfolio, such as Class IIa, Class IIb and Class III under MDR (EU 2017/745), the products face stringent regulatory requirements. Compliance involves:

- CE marking through conformity assessment with a notified body;
- Comprehensive clinical evaluation requiring robust clinical data and validation trials;
- Post-market surveillance systems, including real-world evidence collection and risk management updates;
- Appointment of a Person Responsible for Regulatory Compliance (PRRC) to assess quality and safety documentation.

For SMEs like Ventijet, the MDR introduces significant challenges. The cost of clinical trials, the limited availability of notified bodies, and the extended certification timelines increase both financial and operational pressures. Delays in CE marking also postpone revenue generation, heightening the importance of external financing. Nonetheless, MDR compliance also enhances trust and international competitiveness, as meeting EU standards facilitates recognition in global markets.

E. Financing and investment

To sustain innovation and achieve regulatory compliance, Ventijet has structured an ambitious investment strategy. The company has pursued a financing round of approximately €4 million, combining:

- Venture capital funding to secure long-term growth and scaling capacity;
- Industrial partnerships with established players to leverage expertise and market access;
- Public funding mechanisms, such as Horizon Europe grants, national innovation programs, and regional support schemes.

These funding sources are critical to covering the high upfront costs of MDR compliance, including clinical evidence generation, regulatory consultancy, and certification fees. They also allow Ventijet to build collaborative projects with hospitals and research institutions, directly contributing to MDR requirements for clinical data and post-market validation.

F. Synthesis: MDR impact on Ventijet Health Technology

The Ventijet case illustrates the dual impact of MDR on SMEs:

1. Challenges:

- Significant increases in compliance costs;
- Regulatory bottlenecks and certification delays;
- Heightened financing pressures in the pre-market phase;

2. Opportunities:

- Strengthened trust and credibility through compliance with one of the world's strictest regulatory frameworks;
- Enhanced international competitiveness, as MDR certification is often recognized globally;
- Reinforcement of professionalization and collaboration, pushing SMEs to adopt structured regulatory, clinical, and sustainability strategies.

Through entrepreneurial agility, collaborative partnerships, and smart business models, Ventijet demonstrates how SMEs can navigate regulatory burdens without

compromising innovation capacity. This demonstration underscores the importance of aligning entrepreneurship, sustainability, and collaboration to sustain competitiveness in the European medical device industry.

V. Analysis and discussion

A. Impact of MDR on competitiveness

The introduction of MDR (EU 2017/745) has reshaped the competitive landscape of the European medical device industry. From a barriers perspective, the regulation has resulted in longer time-to-market due to extended conformity assessments, additional requirements for clinical evidence, and limited notified body capacity [13]. For SMEs, these bottlenecks often translate into delays in commercialization and a heavier dependence on external financing to sustain operations during regulatory processes. The cost of compliance, including clinical trials, regulatory consultancy, and post-market surveillance, is also disproportionately burdensome for smaller firms [14].

At the same time, MDR creates important opportunities. By raising quality and safety standards enhances patient and clinician trust in European-made devices. This increased trust may support internationalization, as MDR-certified devices often enjoy smoother entry into non-EU markets due to the regulation's global recognition. Moreover, stricter documentation and transparency requirements push companies to adopt more robust quality management systems, thereby improving long-term competitiveness and resilience. Thus, while MDR initially slows innovation and imposes high costs, it can also act as a driver of professionalization, quality, and international credibility.

B. SMEs vs. corporates

The impact of MDR differs substantially between large corporates and SMEs. Large corporations, such as Philips or Dräger, generally adopt a conservative and incremental innovation approach, favouring product line extensions or efficiency improvements rather than disruptive innovation [5]. Their extensive regulatory departments, financial reserves, and established relationships with notified bodies enable them to absorb MDR requirements with relatively less disruption. In contrast, SMEs are agile, disruptive innovators, often focusing on breakthrough technologies that address unmet clinical needs. However, they face significant resource constraints in terms of regulatory expertise, financing capacity, and staff. MDR slows SMEs by extending development timelines and increasing costs, but it simultaneously forces stronger professionalization, pushing them to adopt structured quality management systems, compliance strategies, and collaborative

networks. Relating to Ventijet, the need to navigate MDR accelerated the establishment of formal regulatory roadmaps and funding strategies that strengthened the company's organizational maturity.

This dynamic suggests that MDR may unintentionally favor corporates in the short term, but SMEs that successfully adapt may become more competitive in the long run due to their dual capacity for agility and professionalized compliance.

C. Role of entrepreneurship

Entrepreneurship is central to sustaining SME competitiveness under MDR. Given the high uncertainty and regulatory burden, SMEs must adopt lean development approaches, and minimise costs while focusing resources on high-value innovations. Flexible business models, such as subscription-based services or equipment leasing, enable SMEs to align more closely with hospital purchasing realities and lower the barriers to adoption. Niche targeting allows SMEs to focus on specific patient segments or clinical needs, avoiding direct competition with corporates that dominate broader markets.

The case of Ventijet demonstrates how entrepreneurial strategies combine technological innovation with financial and market strategies. By integrating digital twin technology, Ventijet introduced a disruptive clinical tool, while simultaneously designing an investment plan of €4 million to cover compliance costs and clinical validation. The company also pursued collaborative partnerships with hospitals to both validate its technology and generate MDR-compliant clinical evidence. This highlights how entrepreneurship in medical devices is not limited to technical creativity but extends to strategic financing, collaboration, and market positioning.

D. Collaborative innovation

The evidence shows that SMEs rarely succeed in isolation under MDR; instead, collaborative innovation is essential. Horizon Europe and other EU programs provide structured frameworks for SMEs to partner with universities, research centers, and other companies, allowing them to share R&D costs and access regulatory expertise. Participation in national and regional clusters, such as the Basque Health Cluster, also fosters synergies by creating ecosystems of SMEs, corporates, and healthcare institutions working toward common innovation goals.

Hospitals play a particularly important role as co-developers and early adopters. Their involvement in device development provides SMEs with real-world feedback, early clinical validation, and the clinical data required for MDR compliance. For Ventijet, partnerships with hospitals were central not only to testing the products but also to building the clinical evidence base necessary for CE certification.

Collaborative data-sharing is another critical component. MDR's emphasis on post-market surveillance and real-world evidence generation requires robust data flows, which are best achieved through collaborative networks involving hospitals, regulators, and industry actors. SMEs that embed themselves in such networks gain both compliance advantages and reputational legitimacy.

E. Sustainability dimension

Although MDR does not explicitly target environmental outcomes, it indirectly promotes sustainability by mandating detailed lifecycle documentation, traceability, and transparency. These requirements encourage companies to better understand the environmental and social impacts of their products, aligning with broader EU policies such as the European Green Deal and the Circular Economy Action Plan [9].

For SMEs, sustainability can become a competitive differentiator. By integrating eco-design principles, resource-efficient production methods, and smart monitoring that optimizes hospital resource use, SMEs can position themselves not only as compliant but also as forward-looking partners for hospitals seeking both safety and sustainability. Ventijet's products, for example, improve clinical efficiency and reduce unnecessary interventions, indirectly contributing to sustainable healthcare practices by optimizing resource utilization in intensive care. Thus, sustainability is not just a regulatory by product but a strategic lever that SMEs can use to stand out in a competitive, compliance-heavy market.

F. Novelty and contribution

Beyond documenting MDR (EU 2017/745)'s frictions, our contribution is a tripartite, SME-oriented framework that links (1) innovation capacity (smart functionality, sustainability by design), (2) regulatory adaptation (clinical evidence, post-market surveillance, notified body engagement), and (3) entrepreneurial strategies (servitized business models, collaborative R&D, blended finance). The Ventijet case operationalizes this framework and demonstrates how combining these levers can convert compliance into a credible market signal and a competitive moat for SMEs.

G. Limitations

This study relies on a single, in-depth case, which may limit external validity. While the example is theoretically informative, cross-case variation (e.g., device class, software as a medical device, disposables vs. capital equipment, market maturity) may produce different adaptation patterns. Data are primarily documentary and secondary; future work should triangulate with interviews (clinicians, notified

bodies, investors) and multi-case comparisons to assess generalizability across EU regions and device categories.

VI. Policy and managerial implications

The findings of this study highlight the dual nature of MDR (EU 2017/745) for the competitiveness of SMEs: while the regulation imposes significant barriers in terms of cost, time, and complexity, it also generates opportunities through improved quality standards, trust, and international recognition. To ensure that SMEs can continue to contribute to the European medical device industry's innovation capacity, both policy-level measures and firm-level strategies are required.

The main policy implications of the presented study are as follows:

- Support for SME adaptation - Policymakers should recognize that SMEs face disproportionate burdens in complying with MDR. Public support mechanisms (such as targeted grants, subsidized regulatory consultancy, and fast-track approval pathways for high-priority innovations) can alleviate financial and administrative pressures. These measures are particularly important for devices addressing unmet clinical needs, such as advanced ventilatory monitoring systems.
- Expansion of notified body capacity - One of the most critical bottlenecks under MDR is the shortage of accredited notified bodies. Expanding capacity through accelerated designation of new bodies and harmonized training for auditors would reduce approval delays, benefiting SMEs that cannot afford prolonged time-to-market.
- Bridging measures and proportionality - Policymakers should consider proportional regulatory requirements for SMEs without lowering safety standards. For example, reducing documentation redundancies, harmonizing interpretations across notified bodies, and extending transitional periods for SMEs would help balance innovation with compliance.
- Promotion of collaborative ecosystems - EU and national governments should further incentivize clusters, consortia, and hospital-industry partnerships. Horizon Europe, EIT Health, and national cluster programs already provide valuable platforms, but dedicated SME-focused instruments within MDR implementation could enhance their impact.
- Integration of sustainability into MDR framework - Future revisions of MDR could explicitly integrate environmental sustainability into regulatory assessments, reinforcing alignment with the European Green Deal. For SMEs, this would create incentives to adopt eco-design and lifecycle management as part of regulatory compliance, turning sustainability into a recognized competitive factor.

Furthermore, the main implications of the present research in the managerial field are synthesis in the following:

- Early integration of regulatory strategy - For SMEs, regulatory compliance must be treated as an integral part of product development rather than a post-hoc process. Ventijet's roadmap illustrates the importance of embedding MDR planning into the design, testing, and financing stages of innovation.
- Entrepreneurial business models - SMEs should adopt flexible business models that mitigate market-entry barriers, such as subscription-based services, equipment leasing, or pay-per-use models. These approaches reduce hospitals' procurement risks and accelerate adoption, creating early revenue streams to offset regulatory delays.
- Collaboration as a survival and growth strategy - Managerial teams should actively pursue partnerships with hospitals, universities, and industry clusters to pool resources, access clinical data, and share compliance knowledge. Collaborative innovation not only lowers costs but also enhances legitimacy and credibility with regulators and investors.
- Financing and investor engagement - MDR compliance is capital-intensive. SMEs must proactively design investment strategies that combine venture capital, industrial alliances, and public funding. Communicating MDR readiness and long-term regulatory resilience can strengthen investor confidence and attract strategic partners.
- Sustainability as differentiator - Managers should leverage eco-design, smart monitoring, and resource-efficient practices not only as compliance necessities but also as marketing and positioning tools. By aligning with hospital sustainability goals and EU policy priorities, SMEs can turn sustainability into a competitive advantage.

In addition to the above-mentioned aspects, the analysis demonstrates that MDR does not inevitably reduce SME competitiveness. Rather, its impact depends on the interplay between policy frameworks that alleviate disproportionate burdens and managerial strategies that transform compliance into an opportunity. The Ventijet case shows that with the right combination of entrepreneurship, collaboration, and sustainability, SMEs can overcome the initial barriers of MDR and position themselves as agile innovators capable of shaping the future of smart and sustainable healthcare.

VII. Conclusions

MDR (EU 2017/745) reshapes European Medtech competitiveness by raising evidentiary standards and post-market obligations. For SMEs, this produces near-term frictions (longer time-to-market, higher costs, and constrained access to notified bodies) but it also strengthens long-term positioning through quality

signalling, international credibility, and organizational professionalization. This dual impact highlights the paradox at the heart of the regulation: it can slow down resource-constrained innovators in the short run, yet it may simultaneously enhance the resilience and reputation of those able to adapt.

The comparative dynamics between corporates and SMEs underscore this paradox. Large firms, with greater resources and dedicated compliance teams, can absorb MDR requirements more easily, but often pursue incremental innovation. SMEs, though more vulnerable to regulatory strain, show agility and disruptive potential; MDR pressures them toward greater professionalization and strategic sophistication. Importantly, while sustainability is not an explicit objective of MDR, the regulation indirectly fosters it through lifecycle documentation, transparency, and post-market obligations (opening a pathway for SMEs that integrate eco-design and resource-efficient practices to convert compliance into a competitive advantage).

The case of Ventijet Health Technology illustrates how entrepreneurship and collaborative innovation can mitigate regulatory barriers while turning compliance into a platform for sustainable growth. By mobilizing resources creatively, forging partnerships with hospitals and research institutions, and embedding sustainability and digital intelligence into device design, SMEs can navigate MDR without losing sight of competitiveness.

The main limitation of this study is that it relies on a single case, which constrains the extent to which findings can be generalized. Outcomes may vary depending on device class, technology type, or market maturity.

The novelty of this paper lies in its development of a tripartite framework (linking innovation capacity, regulatory adaptation, and entrepreneurial strategies) specifically tailored to SMEs operating under MDR (EU 2017/745). This framework moves beyond descriptive accounts of MDR's impact by offering a structured lens through which managers and policymakers can transform compliance from a burden into a strategic asset. Future research should test and refine this framework across multiple SME comparison and device types to identify boundary conditions and generate actionable design rules for sustaining competitiveness under the evolving European regulatory regime.

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PREVENTION OF WORK ACCIDENTS IN THE CONSTRUCTION SECTOR: STUDY ON THE ACTIVITY OF SLOPE SUPPORT

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Abstract

Accidents in excavation and slope support remain a critical issue in construction, especially in Romania, where fatality rates surpass European averages. This study examines accident causes and prevention strategies using a mixed-method approach: systematic literature review, statistical analysis (Eurostat and Romanian Labour Inspection, 2014–2023), case studies, and cost–benefit analysis. Results show 187 fatal accidents in Romania during the period, 68% of which were caused by collapses, with a severity index of 8.1, compared to the EU average of 4.7. Case studies revealed contrasting outcomes: wooden supports in a sewer project led to near-miss collapses, mechanized trench boxes in highway works ensured safe operations, and diaphragm walls with real-time monitoring prevented failures and avoided losses exceeding €1.2 million. Cost–benefit analysis confirmed all preventive measures were economically viable, with advanced monitoring reducing accidents by up to 35% and yielding the highest returns. These findings demonstrate that proactive investments in modern safety technologies are both life-saving and financially sustainable. The study highlights the importance of implementing rigorous prevention measures, including staff training, the use of personal protective equipment, continuous monitoring of the condition of embankments and strict compliance with safety regulations.

Keywords

Work accidents; construction; bank support; prevention, occupational health and safety;

I. Introduction

The construction industry ranks among the most hazardous sectors worldwide, with excavation and slope support operations presenting some of the highest accident risks. Fatal trench collapses remain a persistent problem: approximately 73% of victims in excavation accidents die due to slope failure. According to Eurostat (2020), Romania recorded a fatal accident rate of 5.67 per 100,000 workers, nearly triple the EU average of 2.05.

Despite legal requirements and established safety standards, slope support accidents continue to occur due to deficiencies in planning, inadequate monitoring, and insufficient training. This paper addresses the problem by combining technical and economic analysis to demonstrate that prevention measures, though initially costly, are cost-effective in the medium and long term [1,2].

Slope support activities, essential in civil, hydraulic, and infrastructure construction projects, often involve interventions under difficult conditions, on unstable ground, or in areas with a high risk of landslides and collapses. For this reason, workers involved in such operations face numerous dangers that can lead to serious accidents if not properly managed. Preventing work accidents in this field is not only a legal obligation but also a moral and professional responsibility toward the safety of work teams.

This article aims to highlight the main risks associated with slope support activities, analyse the common causes of accidents, and provide practical measures and recommendations for their prevention [3]. Through an integrated approach that includes proper staff training, strict enforcement of safety regulations, and the use of modern protective technologies, safe and efficient working conditions can be created, significantly reducing the incidence of workplace accidents.

II. Methodology

This study adopts a mixed-method approach designed to combine theoretical insights with empirical evidence, ensuring both depth and practical relevance in the analysis of accident prevention in slope support activities.

First, a comprehensive literature review was carried out, focusing on accident-causation models and preventive strategies specifically related to excavation and slope support works. This review allowed the identification of critical gaps between theoretical recommendations and field implementation, as well as the classification of existing preventive measures into technical, organizational, and behavioural categories.

Second, a statistical analysis was conducted using official accident reports obtained from Eurostat and the Romanian Labour Inspection for the period 2014–2023. The analysis focused on the frequency, severity, and causes of accidents in

excavation and slope support works, enabling a comparative perspective between Romania and the broader European Union. This quantitative dimension provided a solid empirical foundation for assessing accident trends and the effectiveness of existing safety measures.

Third, case studies were developed to illustrate real-world practices and outcomes in three types of construction projects: deep excavation works, sewer installation, and large-scale infrastructure projects. In each case, the slope support methods, risk management strategies, and safety practices employed were documented and assessed. This qualitative component offered context-specific insights into how preventive measures are applied under varying technical and environmental conditions.

Finally, a cost-benefit analysis (CBA) was undertaken to evaluate the economic implications of implementing preventive measures. The analysis compared the additional financial costs of adopting advanced technologies, such as mechanized supports, IoT-based monitoring systems, and drone inspections, with the estimated economic benefits derived from accident reduction, including avoided medical expenses, compensation costs, project delays, and material damages. This approach provided a measurable assessment of the financial sustainability of prevention strategies, highlighting the balance between safety investments and project performance.

Through this multi-layered methodology, the study integrates theoretical models, empirical data, and practical evidence to produce conclusions that are both scientifically grounded and economically substantiated.

The first stage of this study involved conducting a systematic literature review following the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency, reproducibility, and methodological rigor. The focus of the review was on excavation safety, slope support methods, accident causation models, and preventive measures in the construction sector.

Search Strategy. The review was based on a structured search of four major academic databases: Scopus, Web of Science, ScienceDirect, and Google Scholar, complemented by institutional sources such as Eurostat, EU-OSHA, and the International Labour Organization (ILO). The search was conducted between January and March 2025 using combinations of the following keywords: slope support OR slope stabilization OR excavation safety, and occupational accidents.

Eligibility Criteria. To ensure the relevance and quality of the material, the following inclusion and exclusion criteria were applied:

- Inclusion criteria: peer-reviewed journal articles, conference papers, official reports, and international standards published between 2000 and 2023; studies focusing on excavation or slope-related safety in construction; English-language sources.

- Exclusion criteria: publications outside the construction sector (e.g., mining), studies without methodological detail, and non-scientific articles (e.g., media reports).

Study Selection. The initial search retrieved 850 records. After removing duplicates (312), 538 records remained for screening. Titles and abstracts were screened for relevance, leading to the exclusion of 488 articles that did not meet the eligibility criteria. The full texts of the remaining 50 articles were assessed; 15 relevant studies met the inclusion criteria and were included in the final synthesis.

From the included studies, data were extracted on: accident causation models, preventive measures, classified into: Technical: slope support systems (wooden shoring, sheet piles, diaphragm walls, mechanized boxes), monitoring technologies, and geotechnical engineering solutions. Organizational: work planning, supervision, safety regulations, and emergency procedures. Behavioral: worker training, safety culture, use of personal protective equipment (PPE).

We also identified gaps, such as limited adoption of monitoring technologies in Eastern Europe, insufficient integration of climate-change-related risks, and the persistent gap between prescribed safety measures and actual implementation on construction sites.

Review Outcomes. The systematic review revealed that while technical standards and guidelines are well developed, accident statistics continue to indicate a high incidence of slope collapses, especially in Romania and other Eastern European countries. The literature highlights that prevention strategies are effective only when supported by a strong organizational culture and continuous monitoring technologies. However, cost-related barriers and lack of enforcement often undermine implementation.

This systematic literature review provided the conceptual foundation for the empirical investigation in later sections of this study. Specifically, it informed the selection of accident indicators for statistical analysis, shaped the focus of the case studies, and guided the economic evaluation of preventive measures.

The research incorporated three in-depth case studies focusing on construction projects where slope support played a critical role. The case studies were designed to capture the practical realities of risk management, going beyond aggregate data to illustrate how preventive measures are selected, implemented, and evaluated on-site.

Case A: Deep Excavation for Sewer Installation in Bucharest.

This project involved a 4.5-meter-deep trench in a densely populated urban area. The support system used was wooden shoring, chosen primarily due to its low cost and the temporary nature of the excavation. However, the documentation revealed that the timber was not uniformly treated or tested for structural integrity.

Interviews with site engineers highlighted frequent concerns about soil instability, especially during periods of rainfall. There were 4 fatalities recorded and two near-miss incidents occurred when partial collapses forced temporary site closures. Safety procedures mainly focused on PPE and manual inspections, while preventive monitoring technologies were absent. Cost savings in material selection were offset by delays and remedial works following the accidents.

Case B: Highway Embankment Construction

The second project involved the construction of a major highway embankment, requiring continuous excavation along a 2-km stretch. Here, mechanized trench boxes were adopted to ensure rapid progress and consistent protection of workers. The rationale for their selection was both technical efficiency and compliance with stricter EU funding safety requirements. Project records confirmed one accident. The main risk identified was equipment misuse during installation and removal, mitigated through strict supervision. Safety practices included mandatory daily briefings and structured rotation of workers to minimize fatigue.

Case C: Metro Extension with Diaphragm Wall Supports.

The third case study examined an underground metro extension in Bucharest that required deep excavations exceeding 20 meters. The project adopted diaphragm wall supports combined with real-time monitoring using sensors embedded in the retaining structures. This advanced system allowed engineers to detect soil movement and water infiltration at early stages. Project documentation revealed that two critical alerts were triggered, prompting timely reinforcement and preventing potential collapses. Interviews with engineers confirmed that without the monitoring system, both incidents could have escalated into major accidents, causing months of delays. Although the preventive measures increased direct costs by approximately 4%, the avoidance of a single collapse, estimated to cost over €1.2 million in damages and delays, clearly demonstrated the economic efficiency of advanced monitoring technologies.

Across the three projects, the case studies underscored that low-cost solutions (Case A) often expose workers to greater risks and generate indirect costs through delays and remediation. In contrast, mechanized and technologically advanced systems (Cases B and C) demonstrated not only superior safety outcomes but also better cost efficiency in the long run. These findings validated the hypothesis that preventive investments, though initially more expensive, yield tangible economic and safety benefits when assessed over the full project lifecycle.

Cost–Benefit Analysis (CBA)

The final stage of the methodology involved applying a cost–benefit analysis (CBA) to evaluate the economic feasibility of the preventive strategies identified during the

literature review and case studies. This stage was essential for moving beyond purely technical discussions and demonstrating the financial rationale for implementing safety measures in slope support works.

The analysis considered both direct and indirect costs associated with preventive strategies. Direct costs included investments in:

- Training programs and worker awareness campaigns, aimed at strengthening safety culture and ensuring compliance with established procedures.
- Personal protective equipment (PPE) and routine safety inspections, representing the baseline level of investment in occupational safety.
- Mechanized support systems such as trench boxes and prefabricated shoring, designed to provide structural stability in excavation projects.
- Advanced monitoring technologies, including IoT-enabled sensors, drone-based inspections, and automated early-warning systems.

Indirect costs, such as administrative efforts, were also factored into the assessment to reflect the total financial burden of adopting these measures.

On the benefit side, the analysis accounted for the measurable economic savings resulting from accident prevention, which included:

- Reduction in direct accident costs, such as medical care, workers' compensation, and litigation expenses.
- Avoidance of indirect costs, including project delays, work stoppages, contractual penalties, and reputational damage.
- Preservation of long-term productivity and workforce well-being, which, while more difficult to quantify, contributes significantly to sustainable project performance.

III. Results and Discussion

The statistical evaluation of occupational accidents in excavation and slope support works provides a clear picture of the risks associated with this activity in Romania compared to broader European trends. Data collected from the Romanian Labour Inspection and Eurostat occupational safety databases for the period 2014–2023 revealed a persistently high rate of fatalities and severe injuries despite gradual improvements in national safety regulations.

Over the ten-year period, Romania recorded 187 fatal accidents in excavation and slope works. A large majority, approximately 68%, were directly attributable to slope or trench collapses, confirming international evidence that ground instability remains the dominant hazard in this type of work. The remaining accidents were related to machinery mishandling, falls, or contact with underground utilities, but their frequency was comparatively lower.

The severity index, measured as the average number of lost workdays per accident, was 8.1 in Romania. This figure is significantly higher than the European Union average of 4.7, indicating that accidents occurring in Romanian construction sites tend to be more serious, often resulting in long-term incapacity or fatality. This discrepancy highlights systemic weaknesses in preventive practices, enforcement, and the use of advanced monitoring technologies.

A breakdown of the main causes of accidents revealed three critical categories:

1. Inadequate shoring or support systems (41%) – including cases where wooden supports were improperly installed, deteriorated, or insufficient for soil pressure conditions.
2. Lack of monitoring and inspection (26%) involving situations where soil movements, water infiltration, or vibrations went undetected until collapse occurred.
3. Insufficient training and safety awareness (18%) reflected in unsafe worker behavior, improper use of PPE, or disregard of safety procedures.

Other contributing factors, though less frequent, included equipment-related accidents during support installation and external conditions, such as heavy rainfall, which intensified slope instability.

When benchmarked against EU data, Romania's accident profile suggests not only a higher frequency of severe accidents but also a greater reliance on traditional and low-cost support methods, often without adequate monitoring or training. The findings underscore that while European averages point to gradual improvement in excavation safety, Romania continues to lag behind, requiring stronger integration of preventive technologies, regulatory enforcement, and worker education programs.

This analysis established the scale of the problem and provided a quantitative foundation for the subsequent case studies and economic assessments. It confirms that without systematic intervention, slope support activities will remain among the most hazardous components of the construction sector.

From the literature review, we extracted the main methods used to ensure ground stability during excavation and the main occupational risks associated with these methods.

Slope support is essential for ensuring ground stability during excavation, foundation, sewer, or infrastructure work. The choice of the appropriate method depends on several factors: excavation depth, soil type, groundwater level, project duration, and weather conditions [5,6].

- Wooden supports (wooden formwork, props, planks, beams), used for temporary, shallow excavations (up to 3–4 m), installed manually, in stages, as excavation progresses. Associated risks: Collapse due to degraded or inadequate wood for soil

pressure; Incorrect installation with weak or unsafe fixings; Landslides in unstable soils or in the presence of water; Risk of crushing during assembly/disassembly.

- Metal supports (prefabricated panels, metal formwork systems, H or I beam), used in medium to deep excavations, including in difficult soils, can be installed with specialized machinery, reusable and highly resistant to pressure. Associated risks: improper handling of machinery, risk of impact or crushing, panel slippage/collapse if not properly anchored, undetected manufacturing defects or wear.

- Sheet Pile Supports (driven, vibrated, or pressed metal sheets), used in urban areas, ports, or works with unstable soils and high groundwater, interconnected sheet piles are vertically driven into the ground, providing good water sealing. Associated risks: excessive noise and vibrations, affect surrounding areas and nearby structures, misalignment or displacement in soils with large stones or obstacles, and accidents involving driving/vibrating equipment.

- Bored Pile or Diaphragm Wall Supports, techniques used in major projects (tunnels, subways, underground parking), involve drilling reinforced concrete piles or casting concrete walls in the ground. Associated risks: Drilling errors: deviation from verticality, insufficient depth; Accidents due to trench edge collapse before full support is in place; Contact with underground utilities (electrical cables, gas pipes).

- Mechanized Support Systems (support boxes, sliding formwork, protective cages), modern solutions for fast and safe excavations (e.g., sewer works), inserted directly into the excavation using excavators. Associated risks: Improper securing in the ground, risk of displacement, Mechanical accidents during installation/removal (being caught between panels, heavy machinery), Incompatibility with site geometry – sloped or irregular soils.

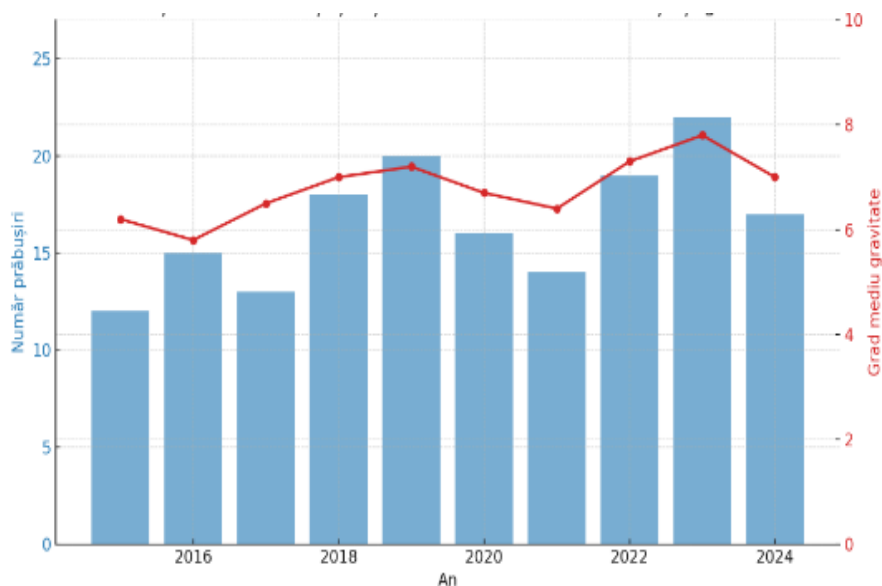
- Sloping (controlled slope without rigid support), used where space allows for a stable slope (e.g., 1:1.5 or 1:2), does not involve support materials – only soil shaping. Associated risks: Instability in soft or wet soils – high risk of sliding; Water infiltration that can erode the slope and cause collapses; Lack of slope monitoring can lead to sudden failure.

Regardless of the chosen method, common risks may arise, as shown in Table 1, which provides an analysis of the main characteristics of the support methods.

A published study on geotechnical works and excavations shows that approximately 58.8% of all accidents during pipe installation and paving were fatal, and around 73% of the victims died due to trench or slope collapses. According to Eurostat data from 2020, Romania recorded a rate of 5.67 fatal accidents per 100,000 workers, compared to the EU average of approximately 2.05 per 100,000 workers. Romania ranked among the top countries in the EU for fatality rates, double the European average and significantly higher than other countries [9]. Figure 1 presents the evolution of the annual number of trench and slope collapses (blue bars) and the average severity level of these incidents (red line, on a scale from 1 to 10) over the past 10 years.

Table 1. Characteristics of Slope Support Methods in Construction

Method	Recommended Depth	Soil Type	Advantages	Disadvantages	Associated Risks
Wooden Supports	< 3 – 4 m	Light/Dry Soils	Low cost, easy to install, flexible for small-scale works	Low durability, unstable in wet or heavy soils	Collapse, crushing, wood breakage, lack of resistance in saturated soils
Metal Supports	3 – 6 m (or more)	Varied Soils	Durable, reusable, adaptable	Higher cost, requires machinery and skilled personnel	Machinery impact, collapse due to incorrect installation, mechanical failures
Metal Sheet Piles	> 4 m	Unstable / Water-Saturated Soils	Good sealing, durable, safe at great depths	Noisy, impact on surrounding structures, expensive	Vibrations, slippage, soil blockages, equipment-related accidents
Diaphragm Walls / Bored Piles	> 6 m	Clays, Mixed Soils	High stability, water protection, suitable for urban areas	High costs and time, complex execution	Temporary collapse, mud failure, drilling errors, contact with underground utilities
Mechanized Systems (boxes, cages)	2 – 5 m	Cohesive / Sandy Soils	Quick to install, safe, reusable	Requires space and adaptation to excavation geometry	Caught between panels, poor adaptation to terrain shape, misuse
Natural Sloping	Variable (depending on slope)	Stable, Dry Soils	No support costs, simple, natural	Requires large space, inefficient in unstable/wet soils	Landslides, erosion, unsuitable for narrow or urban areas

**Fig. 1. Evolution of the Annual Number of Slope Collapses (Source: Eurostat)**

Case Study Findings

To complement the statistical analysis, three case studies were examined in order to understand how slope support methods are applied in practice and how preventive strategies influence both safety outcomes and economic performance.

Case A: Urban Sewer Project in Bucharest

The first case focused on installing a 4.5-meter-deep sewer trench in a densely populated urban area. Due to budgetary constraints and the temporary nature of the work, wooden supports were chosen as the slope stabilization method. While this solution offered low initial costs, the project documentation and interviews with site engineers revealed serious limitations. The timber materials were not standardized for strength and were vulnerable to degradation under moisture conditions. No formal monitoring system was in place, and soil stability was assessed only through visual inspections. Consequently, two near-miss incidents occurred when partial slope failures forced temporary site shutdowns. Although these incidents did not result in fatalities, they caused project delays and additional expenses for remediation, illustrating the risks of relying on outdated support systems without monitoring.

Case B: Highway Embankment Construction

The second case study analyzed the construction of a major highway embankment, involving continuous excavations along a large stretch of terrain. In this project, mechanized trench boxes were used as the primary support method. The rationale for their adoption was the need for consistent protection over long excavation sections and compliance with safety standards tied to EU funding. The use of mechanized systems ensured uniform stability, and strict supervision reduced risks associated with installation and removal. The project reported no accidents or near-misses, despite challenging weather conditions. The additional investment increased project costs by approximately 8% compared with traditional wooden supports, but the prevention of collapses and uninterrupted workflow demonstrated that the higher upfront expense was offset by long-term economic and safety benefits.

Case C: Metro Extension with Diaphragm Wall Supports.

The third case examined a deep excavation exceeding 20 meters for a metro extension project in Bucharest. Here, diaphragm wall supports were combined with real-time monitoring using embedded sensors to detect soil movement and water infiltration. The advanced system successfully identified two critical situations where soil deformation exceeded safe thresholds. Early alerts enabled engineers to reinforce the structure before a collapse occurred. The investment in monitoring and

advanced support systems increased costs by approximately 4%, but by preventing two potential collapses, the project avoided delays estimated at more than €1.2 million. This case illustrates the high economic efficiency of digital monitoring systems, which deliver both safety improvements and measurable financial savings.

The three case studies highlight a clear trend: while low-cost traditional methods (Case A) expose workers to higher risks and generate indirect costs through delays and remediation, mechanized (Case B) and digitally monitored advanced systems (Case C) achieve superior safety and cost performance. These findings emphasize that proactive investment in modern preventive technologies not only reduces accident risks but also enhances the overall economic sustainability of construction projects.

Slope collapses are among the most severe types of accidents, often resulting in fatalities. In Romania, the reduction in the total number of accidents between 2020 and 2024 indicates a downward trend, but the rate remains significantly higher compared to other EU countries. These data highlight the importance of strictly implementing preventive measures and training in slope support operations

Cost–Benefit Analysis Findings.

The CBA revealed clear variations in both cost and effectiveness across the preventive strategies:

- Training combined with PPE resulted in an estimated 10–20% reduction in accidents. The incremental cost represented 0.5–1.5% of total project budgets, yielding modest net benefits. Although relatively inexpensive, these measures alone were insufficient to achieve substantial accident reductions.
- Mechanized support systems raised project costs by approximately 3%, but they delivered a 28% reduction in accidents, producing a high benefit–cost ratio (BCR). These systems proved especially effective for large-scale projects that require consistent excavation protection.
- Advanced monitoring technologies (IoT sensors and drones) added about 4% to project costs but achieved a 35% reduction in accidents. The BCR values exceeded 2.0, making this the most financially advantageous strategy, particularly in high-risk or technically complex projects.

Interpretation. The results confirm that all analyzed preventive measures are economically viable, with BCRs consistently greater than 1.0. Importantly, while low-cost solutions (training and PPE) provide a necessary foundation, technological investments deliver the greatest long-term return by significantly reducing the likelihood of severe incidents.

Thus, the CBA demonstrates that modern preventive strategies are not only technically effective but also economically justified. For large-scale or high-risk construction projects, adopting advanced monitoring technologies can yield

substantial safety and financial benefits, aligning both occupational health priorities and project performance goals.

IV. Preventive Measures to Reduce the Risk of Slope Collapses

In the construction sector, works involving excavations or interventions near unstable slopes carry a high level of risk, especially due to the potential for ground collapse. Such incidents can have serious consequences for worker safety, cause significant material damage, and negatively impact the pace and quality of project execution [7, 8]. For this reason, adopting rigorous preventive measures and applying recognized industry best practices are essential to ensure a safe working environment.

This chapter analyses the main technical, organizational, and individual measures that can be implemented to prevent slope collapses, emphasizing proper work planning, continuous ground monitoring, the use of appropriate support systems, and effective personnel training.

✓ *Assessment and Planning of Works*

Measure	Details
Geotechnical Study	Obtaining a report on soil type (clayey, sandy, unstable, etc.), groundwater level, and natural stability
Soil Risk Classification	Soil is classified based on cohesion and stability (e.g., cohesive, non-cohesive, granular soils).
Slope Angle Calculation	The maximum safe slope without support is determined (e.g., 34° for dry sand, 45° for wet clay).
Technical Design for Slope Support	Any deep excavation or work in unstable terrain must have a dedicated occupational health and safety (OHS) plan.

✓ *Work Organization and Protective Equipment*

Measure	Details
Marking the Risk Area	Clear signage, restricted access for unauthorized personnel.
Control of Heavy Equipment	Prohibition of heavy machinery movement near the edge of slopes
Use of Personal Protective Equipment (PPE)	Helmet, anti-slip boots, reflective vest, safety harness for work below ground level
Continuous Monitoring	Monitoring slope conditions, especially after rain, vibrations, or freeze-thaw cycles
Emergency Exits and Evacuation Plan	Ramps and ladders inside the trench, spaced no more than 7–10 meters apart

✓ *Training and awareness of workers*

Measure	Details
OSH training specific to excavation work	Training must include early warning signs of trench collapse, such as cracks, wet soil, and vibrations
Simulation exercises (drills)	Simulation of evacuation procedures in case of a collapse.
Clear responsibilities for teams	Each team member must know who is supervising the area and who is responsible for reporting hazards

✓ *Continuous inspection and monitoring*

Measure	Details
Daily inspection of the excavation	Pre-work inspection: stability, shoring, and water accumulation
Inspection after weather events	Rain, snow, frost, earthquakes, or vibrations can destabilize the trench walls.
Labor Inspectorate (ITM) control and internal audit	Verification of compliance with OSH regulations (Government Decision 300/2006, Law 319/2006)

Adopting a proactive strategy for preventing work accidents in the field of slope support not only reduces the risk of tragedies but also optimizes overall project costs by avoiding delays, fines, and material damage [10]. The success of this approach relies on close collaboration between engineers, technicians, workers, and authorities, as well as the use of modern technologies and a strong organizational safety culture.

V. Conclusions

This study confirms that slope support activities remain one of the most hazardous components of the construction sector, particularly in Romania, where accident rates continue to exceed European averages. The statistical evidence gathered between 2014 and 2023 revealed 187 fatal accidents, the majority of which, approximately 68 percent were caused by collapses. The severity index, calculated at 8.1 compared with the EU average of 4.7, shows that accidents in Romania tend to be not only more frequent but also more severe, often resulting in long-term incapacity or death. The analysis of accident causes highlights structural deficiencies in practice, with inadequate shoring, lack of monitoring, and insufficient training emerging as the most prevalent risk factors.

The case studies conducted within the research provide context for these findings. The Bucharest sewer project demonstrated the vulnerability of traditional wooden supports and the absence of proper monitoring, which led to near-miss events and costly interruptions. In contrast, the highway embankment project, where mechanized trench boxes were employed, achieved accident-free operations even under challenging conditions, showing that higher initial costs can be justified through greater safety and uninterrupted workflow.

The metro extension case study went even further, illustrating the effectiveness of diaphragm wall supports combined with real-time monitoring technologies. These systems prevented two potential collapses and avoided financial losses estimated at over €1.2 million, despite a modest four per cent increase in project costs.

The cost-benefit analysis reinforced the evidence from practice. Preventive measures such as training programs and personal protective equipment generated modest improvements at minimal cost, but they were insufficient to significantly reduce the risks of collapse. Mechanized support systems and advanced monitoring

technologies, although more expensive, proved to be both technically effective and economically advantageous. In particular, digital solutions using IoT sensors and drones reduced accident rates by up to thirty-five percent, with benefit–cost ratios above 2.0, confirming that prevention represents not only a legal and moral duty but also a financially rational choice.

Taken together, these findings indicate that preventing work accidents in slope support activities cannot rely solely on basic compliance measures. It requires a proactive safety culture, continuous training, and above all, the integration of modern engineering and digital monitoring systems into everyday practice. While such measures may increase project costs by two to four per cent, the long-term benefits, measured in lives saved, accidents avoided, and economic losses prevented far outweigh the initial investments.

The conclusions of this research therefore, point toward a new approach in excavation safety, one that blends technical innovation with organizational responsibility and economic rationality. Improving slope support practices is not simply an obligation to meet regulatory standards; it is a strategic investment in sustainable construction. By embracing this approach, the industry can move closer to the dual goal of protecting its workforce and ensuring the resilience and efficiency of the infrastructure it builds. By adopting these measures and development directions, the construction sector can become safer and more efficient, significantly reducing work accidents and ensuring a healthy working environment for all employees.

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REDUCING THE LIKELIHOOD OF AN EVENT OCCURRING THROUGH AI MONITORING OF ACTIVITIES IN FUEL STORAGE AND WAREHOUSING

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Abstract

The paper analyzes the ways in which artificial intelligence (IA) monitoring of fuel storage and warehousing activities can contribute to reducing the likelihood of hazardous events. By integrating smart surveillance technologies, predictive analytics, and automatic anomaly detection, risks can be identified in real time and prompt corrective measures can be implemented. The study highlights the benefits of using AI in increasing operational safety, reducing human error, and optimizing logistics processes in the energy sector, with a focus on preventing incidents with major potential.

Keywords

Prevention of work accidents; fuel depots; HIRA; artificial intelligence monitoring.

I. Introduction

Fuel storage and warehousing facilities are critical infrastructures within the energy supply chain. They ensure the safe handling, preservation, and distribution of highly flammable and potentially explosive materials. However, these environments are also characterized by elevated risks of fire, explosion, leakage, and occupational accidents resulting from both human and technical factors. The complexity of operations, coupled with the variability of human behavior and

environmental conditions, significantly increases the probability of incident occurrence.

Traditional safety management systems, based on periodic inspections, manual reporting, and static risk assessments, are often insufficient to detect early deviations or weak signals that precede accidents. As industries transition towards digitalization and Industry 4.0 paradigms, there is a growing need for real-time monitoring, predictive analytics, and proactive intervention strategies to enhance operational safety.

Artificial Intelligence (AI) technologies, particularly machine learning (ML), computer vision, and anomaly detection algorithms, have emerged as transformative tools in this context. When integrated with sensor networks, video analytics, and industrial Internet of Things (IoT) architectures, AI systems can continuously analyze data streams, identify unsafe behaviors, detect abnormal process conditions, and generate early warnings before a critical event unfolds.

This paper investigates how AI-based monitoring systems can reduce the likelihood of hazardous events in fuel storage and warehousing environments. The study focuses on developing a proactive hazard analysis for monitoring workers' activities, equipment status, and environmental parameters, with the aim of detecting deviations that could lead to ignition sources, vapor emissions, or human errors.

The HIRA method (Hazard Identification and Risk Assessment) is one of the most widely used modern techniques for identifying and assessing risks in industrial environments. It represents one of the most effective practical approaches and is increasingly adopted by companies operating in high-risk sectors. When implemented correctly, it allows hazards to be identified as early as the operational planning stage, enabling the adoption of appropriate control measures.

II. Presentation of the HIRA Concept

Fuel depots are exposed to a wide range of hazards: from flammable substance leaks and toxic vapor emissions to operational errors, equipment failures, extreme weather conditions, or acts of negligence. By applying the HIRA method, critical scenarios can be analysed, risks associated with each activity (loading, unloading, maintenance, inspections) can be quantified, and rapid intervention or risk elimination measures can be planned from the design phase of the operation [1,2].

The application of the HIRA method can be elevated by integrating it with artificial intelligence systems and industrial sensors (IoT). Data collected in the field (temperatures, pressures, emissions) can be automatically correlated with operational plans and weather forecasts using AI. Thus, the HIRA matrix becomes a dynamic tool that is constantly updated, allowing preventive measures to be adapted in real time.

The risks associated with industrial activities in fuel depots are considerable, especially during loading and unloading operations. The accumulation of flammable vapours or toxic gases, as well as human errors such as incorrect hose coupling, can lead to explosions, fires, or severe intoxications. Modern technologies, especially mobile robotics and artificial intelligence (AI), offer real opportunities to transform the safety paradigm in these environments, shifting from reactive prevention to proactive prevention.

HIRA (Hazard Identification and Risk Assessment) is a systematic method used to identify hazards and assess the risks associated with activities carried out within an organization. It is an integral part of the Occupational Health and Safety Management System (OHSMS) and serves as the foundation for decision-making processes related to accident prevention and improved working conditions. The method is applicable across all industrial sectors and is compatible with international standards such as ISO 45001:2018 [3,4].

The HIRA method involves the following steps:

1. Hazard Identification. Analysing activities, processes, and equipment to detect any potential source of harm.
2. Determining Consequences. Establishing the possible effects of each identified hazard (e.g., accident, fire, poisoning, material damage, etc.).
3. Severity Assessment (S). Evaluating the seriousness of the consequences.
4. Likelihood Estimation (L). Assessing the frequency or chance of the hazard occurring.
5. Risk Calculation ($R = S \times L$). Obtaining a risk score to prioritize interventions.
6. Establishing Control Measures. Measures may include elimination, substitution, isolation, technical or organizational controls, or personal protective equipment (PPE).
7. Monitoring and Review. Reassessing risks periodically or when processes/installations change.

The risk interpretation grid ($R = S \times L$) is structured as follows:

- 1–4: Low risk – Acceptable. Current measures are maintained.
- 5–9: Moderate risk – Improvements needed; measures should be scheduled.
- 10–15: High risk – Immediate action required.
- 16–25: Unacceptable risk – Activity must be suspended until controls are implemented.

The HIRA method is one of the most comprehensive and versatile tools used in modern occupational health and safety management systems. Through its structured approach to identifying and assessing risks, HIRA plays a crucial role in protecting employees, optimizing technological processes, and ensuring organizational compliance with current legal requirements. When applied correctly and supported by continuous staff training, digital tools, and regular assessment

reviews, HIRA becomes a dynamic, adaptable, and indispensable mechanism in any effective workplace accident prevention strategy.

For organizations in high-risk sectors, such as fuel storage and transportation, implementing the HIRA methodology is not just a recommendation, it is a necessity for reducing human, material, and reputational losses.

The HIRA risk assessment matrix combines two essential dimensions: the Severity (S) of possible consequences and the Likelihood (L) of an event occurring. Each cell in the matrix corresponds to a risk level, helping prioritize preventive actions. HIRA is recognized for its systematic nature and cross-sector applicability, making it a fundamental tool in modern prevention strategies. One of its main advantages lies in its ability to anticipate hazards before they result in unwanted events. Table 1 presents the main results of applying the HIRA method in fuel depots [5].

Table 1. Application of the HIRA Method in Fuel Depots

1	2	3	4	5	6	7	8	9	10
Activity	Risk / Hazard	Consequence	S	L	Initial Risk	Preventive Measures	S	L	Residual Risk
A-1: Fall from height	Climbing onto fuel truck tanks	Electrocution, serious injuries – death	5	2	MED	Installation of protective guardrails. Equipping workers with electrostatic personal protective equipment (PPE). Periodic inspection of equipment used for working at heights. Electrical power shutdown.	5	1	MED
A-2: Accumulation of flammable and toxic vapors	Explosion, acute poisoning and/or chemical burns	Death, explosion, chemical burns, serious injuries	5	3	HIGH	Signalling the danger of explosion, electrical hazard, and poisoning. Equipping with sensors for detecting flammable or toxic vapors. Inspection of valves, taps, and other sealing elements.	5	1	MED
A-3: Overfilling or exceeding maximum pressure limits	Explosion or acute poisoning	Death, explosion, chemical burns, serious injuries	5	3	HIGH	Equipping with sensors for detecting leaks and hazardous vapors. Regular verification of existing operating parameters against the values indicated by manometers and sensors.	5	1	MED
A-4: Human errors / non-compliance with work procedures	Incorrect hose connections and/or failure to ground	Explosion, fuel leaks causing chemical burns or poisoning	5	3	HIGH	Training workers on work procedures and specific occupational safety and emergency instructions. Clear marking of connection elements using different colors or signs. Equipping workers with appropriate electrostatic and waterproof personal protective equipment (PPE), according to the PPE allocation list.	5	1	MED
	Welding, maintenance, electrical inspections	Explosion, chemical burns, or acute poisoning	5	3	HIGH	Ensuring through control and supervision that maintenance teams carry out work with authorized personnel, following work procedures and wearing appropriate personal protective equipment (PPE).	5	1	MED
	Working in confined spaces with insufficient ventilation	Asphyxiation – death – acute poisoning, chemical burns	5	2	MED	Training workers on working in isolation conditions. Establishing a communication procedure with another person at least every 10 minutes.	4	1	LOW
A-5: Omissions	Failure to use PPE	Serious injuries	5	3	HIGH	Training workers on the importance and correct methods of using, storing, and inspecting personal protective equipment (PPE). Inspecting and sanctioning workers who do not wear PPE or do not use collective protection equipment (CPE)..	5	1	MED
A-6: Waste disposal	Soil contamination with hazardous substances	Pollution	3	3	MED	Use of selective waste collection bins. Training workers on types of waste, methods of collection, and how to differentiate between regular and contaminated waste.	2	1	LOW

In the context of analysing workplace accidents in the fuel storage and distribution sector, the application of the HIRA methodology (Hazard Identification and Risk Assessment) proves to be a fundamental tool for preventing and reducing occupational risks. Both from the theoretical perspectives presented in the HIRA assessment and from the examination of documented real incidents, several key conclusions emerge regarding the usefulness and effectiveness of this concept in practice:

- It enables a systematic approach to hazard identification.
- It provides a realistic framework for prioritizing interventions.
- Many of the reported accidents, especially those of human origin, such as failure to use personal protective equipment, incorrect handling of tank wagons, or lack of training, can be anticipated and prevented [6].

The HIRA method gains additional value when complemented by detection technologies, such as robots with emission sensors, thermal cameras, SCADA systems, and predictive analysis software. Correlating this data with the HIRA assessment allows not only for preventive diagnostics but also for a rapid and precise response in case of an incident. This significantly reduces the likelihood of major accidents occurring or escalating

III. Application of AI in Accident Prevention in Fuel Depots

As the complexity of operations in fuel depots increases, the use of advanced technologies becomes essential to ensure a safe, predictable working environment. Artificial Intelligence (AI) offers highly useful tools for both real-time monitoring of ongoing activities and for correlating field data with documentation and external conditions.

Two main directions for applying AI in this field are presented below:

One of the most promising applications of AI lies in the continuous monitoring of activities within the depot perimeter. By integrating smart video cameras, proximity, temperature, vibration, and gas sensors, AI can analyse behaviours in real time and detect deviations from standard procedures [7].

For example, systems can automatically identify if a worker is not wearing personal protective equipment, if a vehicle is parked in a restricted area, or if a loading operation is taking place outside the allocated hours. These technologies can send instant alerts to the control room or occupational safety officers, significantly reducing response time and the likelihood of hazard escalation.

Additionally, through machine learning algorithms, AI can learn normal activity patterns and flag atypical behaviours, predicting potential incidents or human errors before they occur. The second major direction for AI use is the integrated analysis of data from multiple sources: industrial sensors, thermal cameras, inspection drones, maintenance records, operation logs, and weather data.

Using AI algorithms, all this disparate data can be interconnected into a centralized system that analyses risks in real time and proposes customized preventive measures. For instance, if AI detects a rising temperature in a depot area, finds in the database that the last maintenance of the pump in that area was delayed, and weather conditions indicate a heatwave, it can generate an automatic warning for a controlled shutdown of operations [8,9].

This contextual correlation offers a clear advantage over traditional methods, which rely solely on scheduled inspections or post-incident interventions. Moreover, AI can propose dynamic predictive maintenance plans and automatically manage revision decisions based on equipment history, usage intensity, and external factors such as humidity, wind, or atmospheric pressure - critical in a fuel depot where fuel vaporization can reach dangerous levels.

IV. Proposed AI Measures for Reducing the Likelihood of an Incident

To understand the practical applicability of AI in occupational safety, it is important to highlight some of the most relevant ways in which technology contributes to accident prevention. These measures are currently being implemented in the oil and fuel storage sectors:

AI-powered intelligent video surveillance systems. Behavioural analysis cameras automatically detect violations of safety rules, such as lack of PPE, access to restricted areas, dangerous crowding, or improper use of equipment. AI learns normal activity patterns and signals abnormal behaviours in real time.

Crawler-type robots for ground inspections. In high-risk areas such as tanks or technical galleries, crawler robots equipped with multiple sensors (temperature, gas, vibration) can be used to collect data from inaccessible or dangerous zones. Controlled by AI algorithms, these robots send alerts if they detect leaks, cracks, abnormal temperatures, or explosive atmospheres.

Correlation of field data with predictive maintenance. AI simultaneously analyses data collected from industrial sensors (pressure, flow, temperature) and correlates it with maintenance history. If it detects abnormal equipment operation and overdue maintenance, the system can trigger automatic alerts or temporary shutdowns until the issue is resolved, thus preventing accidents caused by wear or ignored malfunctions.

Integration of weather data into risk analysis. AI systems can retrieve real-time weather data (wind, temperature, humidity, atmospheric pressure) and correlate it with operational risks. For example, during strong winds or heatwaves, AI can restrict high-risk operations such as fuel transfer or opening inspection hatches to prevent flammable vapor clouds or accidental explosions.

AI expert systems for decision-making in critical situations. In emergencies (leaks, fires, pressure variations), AI systems can quickly evaluate multiple possible

scenarios and propose automated decisions such as stopping pumps, activating emergency ventilation, closing valves, or rapidly notifying emergency services. This eliminates delays and reduces human error under stress.

The risks associated with industrial activities in fuel depots are significant, especially during loading and unloading operations. The accumulation of flammable vapours or toxic gases, along with human errors like incorrect hose connections, can lead to explosions, fires, or severe poisoning. Modern technologies, especially mobile robotics and AI, offer real opportunities to shift the safety paradigm from reactive prevention to proactive prevention [10,11].

These proposed measures address an urgent need in fuel handling safety. By integrating environmental sensors, AI, and mobile robotics, hazards can be anticipated, context analysed, and real-time alerts issued. These solutions do not fully replace human supervision but provide critical redundancy under operational stress. Investment in AI systems is justified by the reduction in incidents, material losses, and risks to workers' lives.

V. Conclusions

The application of Artificial Intelligence in preventing workplace accidents in fuel depots marks a fundamental shift in the operational safety paradigm. AI is not merely an extension of existing monitoring capabilities it completely transforms how risks are perceived and managed.

With its ability to analyse large volumes of data in real time from industrial sensors, smart cameras, maintenance records, and weather forecasts, AI offers a holistic, dynamic, and anticipatory view of potential hazards.

Moreover, AI acts as an expert system that complements human intervention, significantly reducing the chances of evaluation errors or delayed reactions in critical moments. In a field like fuel storage, where a single incident can cause massive human, financial, and environmental losses, speed and accuracy of response are vital. AI thus contributes not only to early anomaly detection but also to effective prevention through intelligent, automated corrective actions [12,13].

At the same time, through continuous learning and adaptation to the specifics of each facility, AI systems can become trusted partners for safety and maintenance teams, offering predictions based on historical behaviour and current context. Integrating these technologies with traditional risk assessment methods like HIRA, provides a hybrid approach of maximum efficiency and responsibility.

In conclusion, the use of AI is not just a viable option but an urgent necessity in modernizing prevention systems in high-risk facilities. Implementing these solutions in fuel depots represents a decisive step toward an organizational culture focused on active prevention, predictive management, and sustainable safety across all operational components.

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INTEGRATING PHYSICAL EXERCISES INTO ORGANIZATIONAL FRAMEWORKS AND THEIR IMPACT ON ORGANIZATIONAL PERFORMANCE

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Abstract

In the context of the current business environment, organizations are seeking innovative methods to promote a healthy organizational culture and improve employee performance. This research analyzes the potential impact of integrating physical exercise into the workplace in relation to organizational performance. By examining existing models and reviewing the specialized literature, the study highlights the benefits that physical activity can bring to employees' mental health, as well as to job satisfaction and productivity. Additionally, the barriers and challenges in implementing workplace physical activity programs are discussed. The analysis conducted in this paper emphasizes whether promoting an active lifestyle within organizations leads to the creation of a positive work environment and the improvement of overall performance. Through this research, we investigate this relationship by analyzing how employee satisfaction and team cohesion are influenced by organizational wellness initiatives. The present study is based on an interdisciplinary approach, combining perspectives from work psychology, organizational management, and occupational health, in order to highlight the real impact of an active lifestyle on organizational dynamics.

Keywords

Work quality; physical exercise; employee health; organizational performance; organizational culture

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I. Introduction

In the current context, characterized by accelerated changes, digitalization, intense competition, and increased pressure on human resources, organizations are

increasingly concerned with identifying sustainable solutions to support employee performance and well-being.

Physical activity is no longer seen as a secondary initiative but as an essential component of modern organizational culture.

Specialized studies indicate that regular physical exercise can significantly improve employee well-being, reduce symptoms associated with chronic stress, and contribute to the development of stronger interpersonal relationships in the workplace.

Moreover, organizations that encourage movement among employees often observe direct benefits in terms of productivity, engagement, and staff retention.

Exercise tends to support health, yet guidance on building it systematically into organizations is thin. Contributions often stop at description or pilots, leaving scalability and adaptation underexplored.

Despite indications that workplace activity helps, a unified, scalable model weaving behavior change, nature-based elements, and workspace design is still missing. Few comparable studies show multi-level programs shifting standardized pre/post-performance in ways that hold across cultures. This paper tackles that gap through the Integrative System of Adaptive Activation framework (ISAA) and a simple, practice-ready evaluation approach.

From here, three questions guide the study's scope and applied relevance:

- To what extent can workplace physical activity enhance both individual well-being and organizational performance?
- How can organizations integrate physical activity into existing frameworks with minimal disruption and cost?
- What barriers and contextual factors may limit the implementation of such initiatives?

By answering these questions, the paper aims not only to advance theoretical understanding but also to provide actionable insights. Designed to work in both small and large organizations, the framework is broadly usable. We test it using three practical questions tied to our interventions and pre – post measures.

Research question 1: How much do short “Booster Breaks” improve well – being and focus – immediately and across the workday?

Research question 2: Compared with similar indoor breaks, do nature-based (outdoor/green) activities lower perceived stress and strengthen team cohesion?

Research question 3: Do adaptive spaces boost engagement and ease exhaustion – and is perceived postural autonomy the pathway?

These questions map onto the three intervention models detailed in Section 3 – Booster Breaks, Green Exercise, and Adaptive Space – and to the evaluation indicators summarized in Table 2; a model – specific physiological rationale is outlined in Table 3.

We conceptualize an original model that supports healthy work ecosystems without sacrificing competitiveness.

II. Literature review and theoretical background

Specialized literature consistently supports the idea that physical activity is associated with physiological and psychological benefits that directly affect organizational performance. Employees with an active lifestyle tend to exhibit lower levels of stress, better cognitive capacity, improved concentration, and more stable affective states. All these elements synergistically contribute to increased productivity and sustained engagement in professional activity [4, 5].

Regular physical exercise is associated with a lower risk of chronic conditions that affect absenteeism and costs [13]. From an organizational-psychology perspective, physical activity supports mood, motivation, and engagement; physically active employees report higher well-being, stress resilience, adaptability, perceived fairness, and better teamwork, and are more likely to stay with the organization [7, 19]. In short, physical activity contributes to organizational performance.

Organizations that invest in physical-wellness programs signal care, health-oriented values, and responsible leadership; such initiatives can embed into culture and strengthen trust, support, and collaboration [23]. Implementations like active breaks or dedicated spaces are often linked to higher satisfaction, fewer conflicts, and stronger cohesion [3].

Another essential aspect is the prevention of the harmful effects of sedentarism and professional overexertion. Given that most office tasks require static positions for prolonged periods, disorders associated with “Office Syndrome” are increasingly common — characterized by muscle pain, chronic fatigue, impaired vision, and reduced concentration. Organizational ergonomics studies show that active breaks, stretching exercises, or simple posture changes significantly reduce the risks associated with this syndrome and contribute to maintaining postural and mental health [11, 18].

Beyond individual benefits, physical activity also plays a strategic role in positioning modern organizations. Companies that include physical wellness initiatives in their benefits packages are perceived as more attractive to employees and are better able to attract and retain valuable talent. A meta-analysis of workplace physical activity interventions shows that the most common strategies include providing on-site fitness facilities, supervised exercise programs, and motivational or educational sessions. These data illustrate the diversity of approaches organizations can adopt, suggesting that effectiveness depends not on a universal formula but on tailoring programs to specific organizational contexts. [16].

Recent empirical evidence further supports these findings: a 12-week workplace program for sedentary employees significantly improved general health, vitality, social functioning, and mental health [20]. A systematic review indicates that adherence to workplace physical-activity programs is shaped by motivation, personalization, baseline activity levels, and the quality of the work environment [18]. Evidence from the Romanian context further shows that physical and social features of the workplace, together with managerial support, significantly influence employee well-being [8].

Flexible workspaces encourage natural movement, reduce postural strain, and support a positive climate [14, 17].

Effectiveness depends on leadership support, culture, and available resources [15]. Small and medium-sized enterprises may face scalability and infrastructure constraints, and some employees may resist routines perceived as disruptive.

Empirical evidence illustrates both the opportunities and the challenges. For instance, a large multinational technology company reported a decrease in absenteeism and an increase in employee satisfaction after implementing structured wellness programs [2, 22]. However, such results cannot be assumed to apply universally; they must be adapted to the maturity, resources, and cultural context of each organization. These findings underline the importance of tailoring physical activity initiatives to organizational constraints while maintaining strategic alignment with long-term performance goals.

III. Conceptual model and implementation logic (ISAA)

Based on these theoretical foundations, the present research proposes integrating adapted conceptual models that illustrate different ways to incorporate physical activity into the professional setting: from short, structured breaks aimed at stress reduction to outdoor exercises or adaptable spaces that promote occupational health. These models are analyzed based on the impact they generate on the employee, the team, and the overall performance of the organization.

Integrating physical activity into organizational life is no longer merely a trend among innovative companies, but a necessity arising from current workplace realities. The rise in sedentary behavior, persistent occupational stress, the decline in authentic interactions, and increasing levels of professional disengagement are just some of the factors that shape the need for interventions targeting not only productivity, but also mental health, team cohesion, and overall workplace satisfaction [10].

What follows are three theoretical models offering complementary perspectives on how physical movement can be integrated into organizational culture.

The first model offers short, regularly scheduled breaks during the workday, in which employees engage in light physical exercises. Referred to as “Booster Breaks,”

these breaks are designed not only to reduce sedentarism but also to improve mood and maintain mental energy throughout the workday. [9]

Implementing this model requires a shift in how breaks are perceived in the organizational context – from being regarded as ‘lost time’ to being understood as a strategic investment in employee performance. The positive effects of this type of intervention are multiple: improved mood, reduced muscular tension, increased brain oxygenation, lower cortisol levels, and consequently, better focus on tasks. Studies show that employees who consistently participate in such programs report higher job satisfaction and a more positive attitude toward the organization [21].

The second model is based on the idea that nature has a strong restorative effect on the human mind, and therefore proposes outdoor physical exercises, in natural environments, combining the benefits of movement with those of contact with nature. Contact with nature has been associated in numerous studies with reduced mental fatigue, improved concentration, and decreased depressive symptoms [12].

Companies that actively promote outdoor exercise demonstrate commitment to employee well-being and enhance their public image. In this context, “green exercise” becomes not only a wellness intervention, but also may improve employer attractiveness and retention. The workspace is not neutral; it can directly influence professional behaviour by fostering positive attitudes or, conversely, by generating rigidity and psychological discomfort. Adaptive space involves the development of flexible work environments in which employees could adjust elements such as furniture position, lighting, temperature, or space configuration according to current needs. This flexibility is not a luxury, but a form of autonomy that enhances comfort and reduces the effects of organizational stress [11].

Organizations that adopt this model facilitate integrated movement: alternative working postures, walking meetings, and brief recovery areas. Studies in such spaces report higher engagement and work quality, better peer relations, reduced chronic fatigue, and higher satisfaction. In this context, physical exercise is associated with higher individual well-being and improved team functioning, and this balance is essential in a professional environment increasingly marked by burnout, declining loyalty, and emotional instability [18].

The models analyzed – Booster Break, Green Exercise, and Adaptive Space – demonstrate that movement in organizations is more than just a human resources benefit: it is a form of investment in the team’s psychosocial capital. While the active break model addresses basic behavioural needs (daily movement, cognitive disconnection, spontaneous socialization), the other two models go further, exploring the relationship between environment and professional identity.

Outdoor exercise has a dual effect: physiological and symbolic. Physiologically, because it reduces cortisol and reactivates mental resources; symbolically, because it conveys the idea that the organization can take the employee out of the

bureaucratic space and recognizing their fundamental human needs – movement, natural light, connection with the environment. [19]

Transforming the workspace into a factor that actively supports occupational health represents a major shift, as it changes the traditional view of the office as a static setting for work. In this sense, the workspace directly shapes employee behavior: it can encourage or limit movement, support comfort or, on the contrary, create constraints. Studies on active workspaces confirm that employees who can choose their place and posture of work (standing desk, relaxation area, indoor green space, etc.) report higher levels of professional satisfaction, engagement, and energy in creative tasks [14]

The following aspects are also important:

- Movement supports emotional balance and reduces stress. Short breaks lower accumulated tension, outdoor walks aid in cognitive restoration, and ergonomic spaces reduce the physical sources of emotional discomfort.
- Physical activity enhances social cohesion. Collective interventions, especially informal ones, contribute to building authentic relationships among colleagues, reduce latent conflicts, and strengthen the sense of belonging [21].
- In the context of today's competition for talent, an organizational brand focused on physical and mental well-being has a greater chance of attracting high-quality employees and retaining the existing valuable ones [12].

These models are not only a theoretical synthesis but also a practical perspective on how organizational performance can be redefined. From an interdisciplinary viewpoint, performance does not result solely from individual effort but from the balance between body, environment, and relationships. In work psychology, the "social energy" of teams is often discussed, and movement – especially in group formats – is associated with improved team climate and collaboration [13].

Organizational case reports describe improvements in absenteeism and satisfaction following structured wellness programs, yet effects vary by context and program design [17].

Exploring the three models analyzed in this paper allows for shaping an integrative perspective on how physical activity can be introduced and sustained within organizational frameworks, in a coherent manner tailored to the current needs of employees and the global socio-economic context.

The proposed models reflect different facets of the relationship between physical exercise and organizational performance, and through their complementarity, they open up a broad framework for action:

- Model 1 – Booster Break can be implemented without high costs, does not require complex infrastructure, and can be supported through a simple reorganization of the work schedule. It also introduces a strong social element: the short exercise session can become a pretext for informal interaction, group cohesion, and mutual support among colleagues. The benefits have been confirmed by

multiple studies showing that light physical activity performed regularly during work hours reduces cortisol levels and improves cognitive alertness;

- Model 2 – Green Exercise, through outdoor physical activities, has a dual impact: on one hand, it reduces accumulated mental fatigue; on the other hand, it stimulates feelings of freedom, vitality, and connection with one's body. Moreover, interaction with nature enhances intrinsic motivation and creativity, offering an ideal setting for reflection and clarification of strategic thinking;

- Model 3 – Adaptive Space [14] is built on the idea that space induces specific behavior – a notion confirmed by multiple studies in the fields of ergonomics, neuroarchitecture, and environmental psychology.

Additionally, this model sets the foundation for a cultural shift: from a static, results-driven organization to a dynamic one where process and well-being are valued just as highly as performance objectives.

Building on the analysis of the three models and the interdisciplinary perspective proposed in this paper, we support an original contribution in the form of an Integrative System of Adaptive Activation (ISAA) – a strategic framework that enables the progressive, tailored, and scalable implementation of physical exercise within organizations.

We consider the three models to be complementary:

- Booster Break is suitable for short-term daily activation;
- Green Exercise provides a higher level of restoration and creativity;
- Adaptive Space offers a continuous framework that supports healthy behaviour.

Ideally, these models should be combined into a coherent strategy tailored to the organizational profile.

In developing the ISAA model (Integrative System of Adaptive Activation), we found it necessary to incorporate the perspective of Eliyahu M. Goldratt and the Theory of Constraints (TOC), which provides a strong theoretical framework [6] and serves as a connective thread between the conceptual models analyzed and the integrative architecture of the ISAA.

Goldratt's perspective begins with the assumption that every system, regardless of its scale or complexity, operates under at least one key limitation that prevents it from reaching higher levels of performance. In other words, no matter how efficient or well-structured an organization may appear, there is always a weakest link that defines the boundaries of its overall capacity. Real improvement, therefore, does not come from making changes everywhere at once, but from carefully identifying that main constraint, using it as a leverage point, and restructuring processes around it. The classic sequence proposed in the Theory of Constraints – identify, exploit, subordinate, and elevate – offers a disciplined way to continuously push the limits of performance. When this logic is applied to workplace physical activation, the constraint may take many forms: chronic cognitive fatigue caused by long periods of sedentary work, declining motivation due to lack of variety in routines, or even

rigid workspace design that restricts movement and postural flexibility. By diagnosing such constraints, organizations can target their interventions more precisely. For example, short active breaks can be used to relieve mental strain, outdoor sessions can restore emotional energy and cohesion, and adaptive spaces can remove the structural rigidity that fuels exhaustion. In this sense, movement is no longer viewed as a simple wellness initiative, but as a strategic lever that addresses bottlenecks within the organizational system. The principle challenges managers to ask not just if physical activity is useful, but where exactly it can unlock blocked energy and how it can transform a limiting factor into a new source of growth and resilience [6]

ISAA is a strategy to progressively release bottlenecks by adding physical and mental energy where the system is stuck.

For example: Booster Breaks relieve cognitive strain from repetitive work; Green Exercise restores emotion and attention when indoor settings fall short; Adaptive Space removes spatial/postural limits. In short, movement is an active lever for unblocking organizational problems, not just a wellness add-on. ISAA turns this into a practical matrix: each level targets a specific constraint and enables a focused intervention to unblock the system. You don't fix everything at once – you act on the single constraint that causes the biggest loss (productivity, exhaustion, absenteeism, or morale). The model is modular for pragmatic rollout and strategic because it follows TOC logic: intervene where it hurts most.

The ISAA cycle structures our interventions and their pre-post evaluation, as shown in Figure 1.

ISAA is more than a method – it is an operational philosophy: introduce physical activation gradually, precisely and strategically. It runs a chain of adaptive interventions to remove hidden physical, psychological and organizational constraints.

The model adapts the activation path to your organisation's maturity, resources, and culture. If you're not ready to build adaptive spaces, begin with quick wins – small, low-cost pilots that you can measure and repeat. Track simple indicators like participation, frequency, and feedback so you know what's working. It is organised into three operational levels that match increasing depth of physical-activity integration.



Fig. 1. ISAA conceptual model and implementation logic

A. Behavioural Activation – the foundational level of conscious physical routine

- Promote brief, repeated micro-movements during the workday (5–10 min): short active breaks, quick stretches, app workouts, mini team challenges, or adding movement into tasks
- Goal: make movement habitual – a kind of behavioural “hygiene” that fights chronic sitting and keeps work energy up
- Main benefit: it’s highly accessible – works in any organisation, big or small, with minimal resources, so it’s perfect for teams piloting wellness initiatives

B. Environmental Activation – the stage of restoration and nature-based reconnection

- This level adds simple ways to reconnect people with nature – short outdoor walks, meetings outside, or green breaks – to capture the benefits of outdoor activity
 - Goal: brief nature exposure to restore attention, reduce stress, and spark creativity – especially useful for high – pressure or cognitively demanding teams
 - Needs more planning and manager support than level 1 but yields bigger team gains and strengthens the organization’s health-focused brand

C. Structural Activation – enabling environments for sustained movement

- The third ISAA level redesigns the workspace to support movement and postural choice – using adjustable furniture, mobile/standing stations, and quick exercise or recovery areas
 - Design space, micro-movements, and brief recovery breaks; clear norms and leadership make adoption easy
 - Make wellbeing strategic: fund it, assign owners, embed movement/green breaks/adaptive spaces, and track with quick pre/post checks
- ISAA applies Goldratt’s logic across three approaches to find the bottleneck and run fast design–test–scale cycles with pre/post checks.

The toolkit translates the ISAA framework into a set of concise, practical guides and small-scale pilots. Each pilot follows a simple logic: establish a clear baseline, test one focused intervention, measure its effects, and then decide whether to continue, expand, or discontinue it. Designed with limited budgets and time in mind, the toolkit helps organizations direct their efforts toward the main performance constraint identified in their system (as shown in Table 1).

Table 1. Structure of the ISAA model (Integrative System of Adaptive Activation)

Stages	Actions
1. „Identify the dominant organizational constraint” [1]	I. Behavioural: low movement II. Environmental: no recovery spaces III. Structural: limited mobility
2. „Exploit the constraint” [1]	Tactics used: If the issue is cognitive → Booster Breaks (guided active pauses) If it is emotional and relational → Green Exercise (outdoor activities) If it is spatial and postural → Adaptive Space (ergonomic reconfiguration)

3. „Subordinate the rest of the system” [1]	Align processes and workflows. Needs: change management; leadership buy-in; routine redesign; training & comms (the “why”).
4. „Elevate the constraint” [1]	After evaluation, practices are budgeted, validated by feedback/metrics, and moved from pilot to standard.
5. „Search for a new constraint” [1]	Each iteration of the ISAA model can reveal new opportunities: • A latent cultural barrier may emerge (e.g. change resistance) • It may be an equity issue in access to friendly movement spaces • Or a digital innovation opportunity may arise

D. Discussion

Unlike one-track models, ISAA unifies all three levels. It treats employees as bio-psycho-social and the organization as a system that can enable or hinder well-being.

What sets ISAA apart is its modular design. Each organization chooses an entry point—Booster Breaks, Green Exercise, or Adaptive Space—based on its dominant constraint and resources.

Steps can be added in stages, scaled when they work, or paused when they do not. Decisions are guided by pre–post evidence and local fit, not by a fixed sequence. In short, the system is adaptive rather than prescriptive.

Moreover, the model can be easily evaluated through specific indicators assigned to each level:

- At the behavioural level: participation rate, frequency of active breaks
- At the environmental level: emotional feedback, perceived stress, collective satisfaction
- At the structural level: use of dynamic spaces, perceived level of autonomy, retention rate

The ISAA model gives leaders a clear way to raise performance by building trust, autonomy, and care—not tighter control. It offers concrete options – Booster Breaks, Green Exercise, and Adaptive Space – and shows how to align routines, space, and norms around them.

Simple pre–post checks track results so teams can see what works and scale it. Managers pick the right entry point, adapt to context, and improve step by step.

We assess impact on three core outcomes – well – being, perceived stress, and motivation – because they are directly tied to day-to-day energy and performance. To do this, we use a short, repeatable questionnaire administered immediately before the pilot (baseline) and again right after it ends (post). Each item is rated on a 1–5 Likert scale and mapped to the corresponding indicator in Table 2, allowing

us to compute simple pre–post deltas and percentage change. Scores are summarized at both individual and team level (mean and distribution), and we flag movement toward the predefined targets (e.g., well-being +20%, stress –20%, motivation +15%).

For transparency and comparability across pilots, we use the same questionnaire and identical scoring rules every time, without altering item wording or scales. All responses are anonymous and reported only in aggregated form (team averages and distributions), which encourages honest feedback and protects individuals. We also keep a simple version log of the instrument and document any procedural notes (timing, sample size, response rate) so results can be read in context. Where nonresponses occur, we apply consistent handling (e.g., listwise deletion for scale scores) and note it alongside the summaries to maintain methodological clarity.

Table 2. Organizational performance evaluation test

Assessed Aspect	Question	Scale	Objective
Well being	How do you generally feel during your workday?	1–5	+20%
Perceived Stress	How stressed do you feel at work?	1–5	–20%
Motivation	How motivated do you feel for your daily tasks?	1–5	+15%
Team Cohesion	How would you rate your collaboration with colleagues?	1–5	+15%

In the pre–post evaluation process, differences can be expressed as a percentage relative to baseline scores. For example, if the average response regarding 'well-being' is 2.8 before the intervention and increases to 3.4 after implementing physical exercises, this results in an improvement of approximately 21%.

Thus, a reference threshold can be established — for example, a minimum improvement of 20% compared to the baseline value. Setting such a target allows a clear quantification of impact and provides a realistic benchmark for validating the intervention. This approach also aligns with recommendations from the specialized literature on evaluating organizational wellness programs.

Table 2 represents a brief Likert-type questionnaire (scale 1–5) that can be applied pre– and post-intervention to assess well-being, stress, motivation, and team cohesion. Although simplified, this tool may be complemented with validated instruments such as the Perceived Stress Scale (PSS-10) or the Job Satisfaction Survey (JSS). Validated instruments such as the PSS-10 [23] and recent studies on job satisfaction further support the indicators proposed in Table 2.

This evaluation is supported by a physiological explanation. Physical exercise activates hormones endorphins, dopamine, serotonin, and oxytocin – which positively influence mood, energy, and social interaction [19], see Table 3.

Table 3. Activated hormones and their impact

Model	Hormone(s)	Psychophysiological effect	Organizational impact
Booster Break	Endorphins, Dopamine	Stress reduction, increased vitality	Energy, focus
Green Exercise	Serotonin, Oxytocin	Relaxation, increased social bonding	Team unity, trust
Adaptive Space	Reduced Cortisol	Mental clarity, sense of autonomy	Less burnout, higher vigor

These interventions can be strategically applied according to the ISAA model. For example, if cognitive stress is predominant, Booster Breaks are introduced; if there is a lack of cohesion, Green Exercise is recommended; if the workspace is rigid, Adaptive Space becomes the solution. In all cases, the role of leadership is essential: the leader supports, normalizes, and amplifies the change. Thus, physical activity is not just a temporary intervention but an essential driver of organizational transformation.

Operational Steps of ISAA (summary):

1. Identify – run the quick – sheet now to get baseline scores for Well-being, Perceived Stress, Motivation, and Team Cohesion. Note the numbers and keep them as your “before” values. (Targets: Well-being +20%, Stress -20%, Motivation +15%, Cohesion +15%.)
2. Search – pick the team/place where the baseline looks weakest or where people are open to trying something small. Keep it simple: one team, one floor, or one shift.
3. Apply – run a short pilot with one low-friction tactic:
 - Booster Break → expect gains in energy/focus (tracks on Well-being, Motivation)
 - Green Exercise → expect more social ease (tracks on Team Cohesion, Well-being)
 - Adaptive Space → expect less burnout and clearer thinking (tracks on Perceived Stress, Motivation). Record the start quick – sheet just before the pilot
4. Subordinate – make it easy: add it to the calendar, set a short routine, tweak the space if needed, and tell people why you’re doing it. Don’t overcomplicate – one clear instruction is enough.
5. Elevate – repeat the quick – sheet immediately after the pilot and compare to baseline. If you see movement toward your targets (the % changes above), keep and scale; if not, drop it and try the next option. Then start again from step 1.

For each pilot, the process can be followed through a simple sequence of steps. The first step is to complete the baseline quick sheet, which provides an initial

picture of key indicators such as well-being, motivation, stress, and team cohesion. Once this reference point is established, a specific team, department, or workspace is selected to carry out the pilot – ideally a setting that is both representative and easy to manage. The pilot itself should then run for a short period of time, usually one to two weeks, with only one intervention introduced so that its effects can be observed clearly. At the end of this period, the quick sheet is completed again, and the results are compared with both the baseline and the predefined targets. If the intervention shows improvements, it can be kept and possibly expanded to other groups; if it does not bring meaningful change, it can be discontinued and replaced with a different approach. In this way, every pilot functions as a straightforward cycle of testing, feedback, and adjustment, helping the organization learn what works best in practice.

E. Limitations

Although the ISAA model offers a structured framework for integrating physical activity into organizations, several limitations should be acknowledged.

First, the model remains primarily conceptual. While supported by evidence from literature and selected examples, its feasibility still requires validation through larger empirical studies.

Second, successful implementation depends heavily on organizational culture and leadership support. In environments with low managerial commitment, wellness initiatives risk facing resistance or becoming symbolic rather than effective.

Third, some interventions – particularly adaptive workspaces or outdoor facilities – involve financial and infrastructural costs that may not be feasible for all organizations, especially small and medium-sized enterprises.

Finally, scalability represents a challenge. What works in large corporations with structured wellness budgets may not directly apply to smaller organizations.

Recognizing these limitations highlights the need for context-specific adaptation, incremental implementation, and ongoing evaluation of the ISAA model.

F. Future Research – Integrating the Chain Method

Future research could integrate the Chain Method into ISAA: originally for optimizing production flows, it can guide placement of active zones by mapping “links” (routes between work areas and activity spaces) so the most-used zones are central and easy to access.

Integrating this method would strengthen ISAA’s structural dimension by systematizing workspace design, making activity more accessible without disrupting work. Future studies should test its impact on accessibility, wellness-program participation, and overall performance.

IV. Conclusion

In today's dynamic context, where mental health, retention, and sustainable performance are priorities, integrating physical exercise at work is no longer a luxury but a necessity.

The research presented in this paper highlights not only the well-documented benefits of physical activity for individuals, but also how it can serve as a tool for transforming organizational culture.

We proposed the Integrative System of Adaptive Activation (ISAA), a modular model with three levels—behavioural, environmental, and structural. It provides a flexible, scalable framework for healthy work ecosystems, adaptable to each organization's resources and culture.

Integrating physical activity into the professional environment is no longer a marginal option, but a natural direction for sustainable development.

This paper is mainly conceptual and lacks field data. Results depend on culture, leadership, and resources, so effects should be validated through controlled pilots. Future work will test ISAA with pre-post and control designs, including cost analysis.

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FROM BPM TO PROCESS MINING: PRODUCTION PLANNING KPI ANALYSIS

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Abstract

Production planning processes are often prone to long waiting times, redundant activities, and inconsistent production rates. Previous research explored the potential of integrating Business Process Management (BPM) with Process Mining (PM) to achieve production planning automation and digitization. This paper extends previous research by evaluating PM tools to analyze production planning Key Performance Indicators (KPIs). Research results include a discovered process map, identification of bottlenecks and key activities, and KPI analysis. The final contribution of this work is related to the potential application of such a solution for performance measurement, product improvement, and overall business enhancement.

Keywords

Business Process Management (BPM); Process Mining (PM); Business Process Automation (BPA); Key Performance Indicators (KPIs); Production Planning Business Process.

I. Introduction

Modern production requires constant improvements and maximum utilization of the latest information and communication technology (ICT). Nowadays, when technology is applied and implemented in all aspects of human life, the manufacturing industry is one of the main areas where ICT could have a great impact [1]. Minimal technological advancements can result in significant improvements in product development and quality. For such reasons, it is important to ensure continuous monitoring, maintenance, and optimization of manufacturing operations, including the production planning process.

Process mining (PM) represents a set of techniques for conducting process-centric analysis, with the power of automated process discovery, conformance checking, and model enhancement [2]. The essential part of process mining is an event log, i.e., a record of process instances. Apart from cases and process activities, an event log can store additional information about events, such as resource data, time elements, and other relevant attributes [2].

While process discovery creates a process model from the event log, conformance checking detects differences between the initial process model and the event log. The model enhancement also uses the event log to correct, expand, or complete the initial process model [2]. Process mining can be used for organizational analysis as well, apart from process model generation. This can provide valuable information about relationships between the company's resources – workers or machines. Additionally, process mining can visualize process attributes, such as production rate and product quantity, and detect potential problems related to process performance [3].

A comprehensive analysis of production processes, including frequency, performance, and social network analysis, can be performed using the process mining methodology. Therefore, process mining is recognized as a way to fully understand production planning processes and identify process inefficiencies. Subsequently, this paper aims to contribute to more efficient production planning by testing the potential of applying process mining and process management techniques in the context of process analysis and optimization.

The authors' first research concerning production planning automation in a mid-sized manufacturing company in Serbia focused on Business Process Automation (BPA) using Business Process Management (BPM) tools, such as Bonita [4]. The final contribution of this paper was a desktop application for semi-automated production planning business process support. The continuation of research evaluated integrating process mining with BPM and presented a conceptual solution for automating production planning processes using a process mining tool, Disco [5]. Specifically, the second research compared the AS-IS process model [5] with the TO-BE process model [4] to detect differences between the actual and desired process behaviour.

The current paper builds on previous research by examining how process mining and BPM enable production planning Key Performance Indicators (KPIs) analysis, apart from process automation. The study was performed on a synthetically generated event log using a simulated dataset related to production planning processes in the mentioned Serbian manufacturing company. The final contribution of this work represents the extension of previous research by adding KPI analysis through process mining. The generated event log contains performance metrics that were used to conduct frequency, performance, social network, and KPI analysis. In

this way, the paper tested the potential of PM and BPM methodologies when used for production planning optimization.

The remainder of this paper is structured as follows. The following section introduces the process mining approach, along with a description of the process mining tools that were used during this research. The third section provides the methodology for researching production planning processes using process mining tools – Disco and ProM. The fourth section presents the research results, i.e., the results of frequency, performance, and social network mining. Additionally, this section presents calculated process and equipment KPIs, such as allocation and quality ratio. Section 4 also describes the recommendations for process enhancement, digitization, and modernization based on research results. Finally, section 5 discusses the key advantages of implementing the PM approach in the manufacturing industry, together with the conclusion of work, limitations of this study, and proposals for future research.

II. Process Mining

In terms of the manufacturing industry, a digital model represents a software representation of a physical system, including all relevant characteristics and dynamics of the system [6]. Simulating such a model enables the analysis of complex systems, along with system configuration and resource allocation [6]. However, these simulations must ensure the model's reliability, i.e., the physical system and its digital model must be aligned. Additionally, data used for model generation must accurately represent the physical system. Lastly, the physical system must maintain the characteristics and rates that were used during model development [6].

At the beginning of the 21st century, process mining was introduced as a new method for data analysis [7]. The combination of techniques related to process mining facilitated digital model discovery, enabled comparison of actual and desired system behaviour, and led to the detection of unexpected issues and process deviations [6].

The digital model is usually presented in the form of a Petri net or some other process notation, such as BPMN or UML diagrams [8]. Such notation is used for mining all possible paths related to the process flow. Apart from the process perspective, process mining covers the organizational perspective regarding the actors who performed the activities, the case perspective that analyzes the process as a whole, and finally, the time perspective that examines the time and frequency of process events [8].

Several process mining algorithms were developed for model discovery support, classified into three main groups: deterministic algorithms, heuristic algorithms, and genetic algorithms. All of the mentioned algorithms provide a process model

based on the event log registered by Process-Aware Information Systems (PAIS) [9]. In addition to process mining algorithms, numerous process mining tools were also introduced since the process mining discipline was first presented, including Disco, myInvenio, ProM, ProM Lite, SNP, etc [8]. These authors used Disco and ProM toolkits to conduct process mining, whose brief introduction is given in the following text.

Disco offers a simple and intuitive framework for visualizing, filtering, and managing event logs. This tool is particularly useful for performing frequency and performance mining due to its high capability for data preprocessing and generating process maps [8]. Disco can also generate a video of the business process's execution, which can be used to identify process bottlenecks [10].

On the other hand, ProM is an open-source tool that enables generating and exploring the business process model using countless available plug-ins. For such reasons, ProM represents one of the most dominant tools for conducting process mining analysis. Research showed that when discussing the IT industry, ProM is especially useful for organizational perspective analyses and conformance checking [8]. However, the difference between Disco and ProM refers to their supported discovery algorithms. While Disco uses the Disco (fuzzy) miner exclusively, ProM supports a variety of discovery algorithms, such as heuristic miner, genetic miner, α -algorithm, etc. Nevertheless, this does not prevent the simultaneous use of both tools [11]. By exporting the event log into XES format in Disco, researchers can import the mentioned XES file into ProM. This enables users to use both Disco and ProM and gain maximum benefits [12].

This paper explores the potential of applying process mining for production planning enhancement, including the KPI analysis. Key performance indicators express quantifiable measurements of the company's critical success factors [13]. These indicators help organizations monitor crucial business processes, including production planning processes. By doing so, organizations can identify potential problems and implement necessary changes to improve production rates and customer satisfaction [13].

The international standard ISO 22400 defines a set of KPIs for performance evaluation in the manufacturing industry. Authors Zhu et al. [13] made further adjustments to the ISO 22400 standard's list of KPIs, intending to make them more suitable for the modern process industry. The mentioned researchers proposed a new KPI framework, i.e., the redefined KPIs, divided into two main groups – equipment performance indicators and process performance indicators [13]. Equipment KPIs are allocation ratio, utilization efficiency, and equipment load ratio [13]. On the other side, process KPIs include throughput rate, technical efficiency, quality ratio, actual to planned ratio, scrap ratio, finished goods ratio, and energy consumption [13].

Process mining software, such as Disco and ProM, enabled the KPIs analysis [14] and production planning enhancement. This can lead to reduced costs, improved product quality, and the accomplishment of strategic goals. The methodology for conducting KPI analysis using modern process mining tools is given in the following section of this paper.

III. Methodology

The aim of applying process mining techniques was to discover and examine the production planning process map, with the additional objective of performing a KPI analysis.

The previous part of the research on the topic of automating production planning processes delivered the first version of the synthetic event log in CSV format [5]. The mentioned event log included the following columns: *CaseID*, *Activity*, *Resource*, and *Timestamp*. However, to perform a KPI analysis, the event log must contain relevant information related to different performance indicators, such as production rates, energy consumption, input material quantities, time elements, etc. For that reason, the event log used in earlier research [5] was modified and extended so that such metrics are included in the KPI analysis. Some of the metrics added to the event log and used for KPI calculation are:

1. Actual Production Rate: The achieved production output per unit time.
2. Maximum Production Rate: The theoretical maximum production output per unit time.
3. Planned Production Rate: The expected production output per unit time.
4. Actual Produced Quantity: The number of produced units.
5. Desired Product Quantity: The expected number of units to be produced.
6. Actual Faulty Product: The number of produced faulty products.
7. Planned Faulty Products: The expected number of faulty products to be produced.
8. Input Material Quantity: The amount of raw material used during production.
9. Energy Consumption: The energy used during production.
10. Planned Operation Time (POT): The scheduled time during which the equipment or process can be utilized.
11. Actual Busy Time (ABT): The actual time needed for process execution.
12. Actual Production Time (APT): The time needed for completing production activities, such as product scraping and assembling.
13. Actual Down Time (ADT): The time during which the equipment or process is delayed due to malfunctions, unavailability of resources, human errors, or other unplanned events.

Additionally, POT, ABT, APT, and ADT are correlated in the following way [13]:

$$ABT = APT + ADT \quad (1)$$

While the start and end timestamp columns represent when each activity started and finished performing, the added time elements are directly affected by the timestamp values. ABT represents the difference between the first and last timestamp in a case, thus summing the time spent on productive and non-productive activities. On the other hand, APT calculates the sum of executing productive activities only, such as product scraping and assembling. ADT is calculated as the difference between ABT and APT, reflecting different types of delays. Finally, POT has a value within $\pm 30\%$ of the ABT, illustrating the desired time for process completion. Furthermore, to bring the event log closer to real industrial production planning processes, stochastic waiting times between activities were also added.

After expanding the event log by the mentioned metrics, the values of each performance indicator were calculated based on the formulas given by Zhu et al. [13]. Then, the KPI values were divided into four categories: *low*, *medium*, *high*, or *extremely high*, completing the event log preparation.

The methodology for performing the process mining and KPI analysis of production planning processes is presented in the following:

1. Importing the event log into Disco: The synthetically generated event log, created using the Python programming language, was imported into Disco as a CSV file.
2. Data preprocessing: Event log filtering using Disco was used to clean the dataset and prepare it for process analysis.
3. Process map discovery: The event log was imported into Disco, and a process map was generated.
4. Frequency and performance analysis: Frequency and performance perspectives of the production planning process were analyzed to detect bottlenecks, long waiting times, and other process inefficiencies.
5. Production planning KPI analysis: In addition to frequency and performance analysis, Disco was used to examine KPIs, including allocation ratio, utilization efficiency, throughput rate, technical efficiency, quality ratio, and scrap ratio.
6. Event log conversion into XES standard format: By converting the event log into an XES file, data is prepared and ready for process mining using ProM.
7. Social network analysis: Since Disco does not support the generation of social networks [11], ProM is used for further organizational review.

As mentioned earlier, the benefits of implementing this solution include process model visualization, identification of the most frequently repeated process activities

and their associated bottlenecks, and social network mining [15][16]. Relevant KPIs were also calculated and presented in this work. Following the research results, differences between the actual and desired process behaviour can be reduced to a minimum.

IV. Research Results

The following text presents the findings related to data preprocessing, frequency, performance and social network mining, and finally, KPI calculation. After importing the event log into Disco, data preprocessing was performed, which included applying the *endpoint* filter to determine the number of orders ending with product storage. Disco showed that 9015 out of 10000 can be declared as completed, i.e., 90% of cases result in final goods being stored. These 9015 cases were then subject to further process analysis.

A. Frequency perspective

Fig. 1 illustrates a fuzzy model of the production planning process generated in Disco. The absolute frequency and mean duration of an activity are given inside rectangles. The numbers next to the lines show the absolute frequency and mean duration of the path connecting two activities. Thicker lines relate to more frequent paths.

Analyzing the production planning frequency perspective given in Fig. 1, it can be concluded that the most frequent activities are Choosing Production Technology, Material Requisition, Production Operation, Product Scraping, Assembling, and Final Quality Control. These activities illustrate essential tasks for successfully delivering final goods. For that reason, their automation and digitization can help the company attain business excellence.

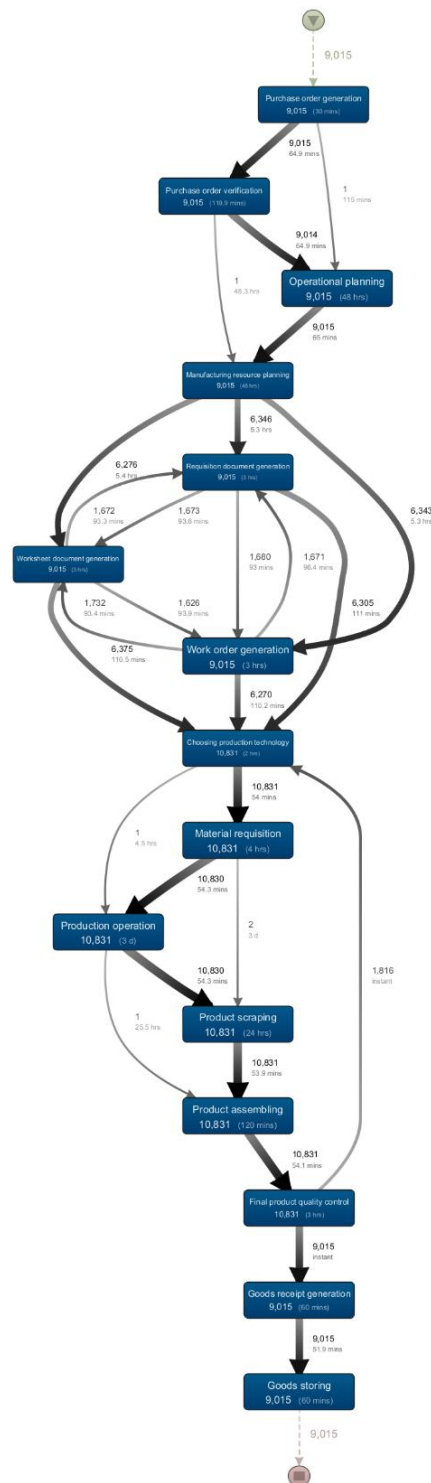


Fig. 3. Production planning frequency mining research results

B. Performance perspective

Fig. 2 presents the performance perspective of the production planning process.

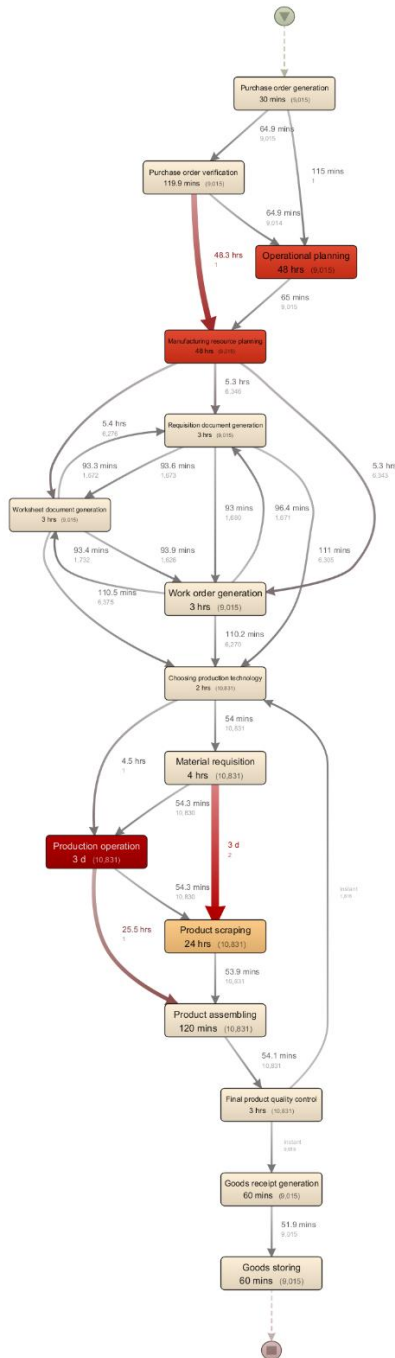


Fig. 4. Production planning performance mining research results

Numbers inside the rectangles indicate the mean duration of activities, while the numbers next to the paths connecting the activities represent mean waiting times. Activities with the longest mean durations are Operational Planning, Manufacturing Resource Planning, Production Operation, and Product Scraping. Furthermore, three bottlenecks are detected whilst analyzing mean waiting times – between activities Purchase Order Verification and Manufacturing Resource Planning, activities Material Requisition and Product Scraping, and activities Material Requisition and Production Operation. To handle these bottlenecks, the company should reconsider implementing automation and monitoring technologies. This could positively influence the production system's throughput and reduce long waiting times.

In addition to frequency and performance perspective analysis, the production planning KPIs were also studied in Disco. The production rate was studied using the *attribute* filter to count the cases where the **allocation ratio** was below 60%. Whether due to resource overloading or unrealistic planning assumptions, the results showed that 38% of cases, i.e., 3814, had an allocation ratio below 30%, while 5022 cases had an allocation ratio ranging between 30% and 60%. Only 179 cases had an allocation ratio above 60%. Fig. 3 presents a statistical overview calculated in Disco for the attribute *allocation ratio*, filtered to include only cases whose allocation ratio was above 60%.

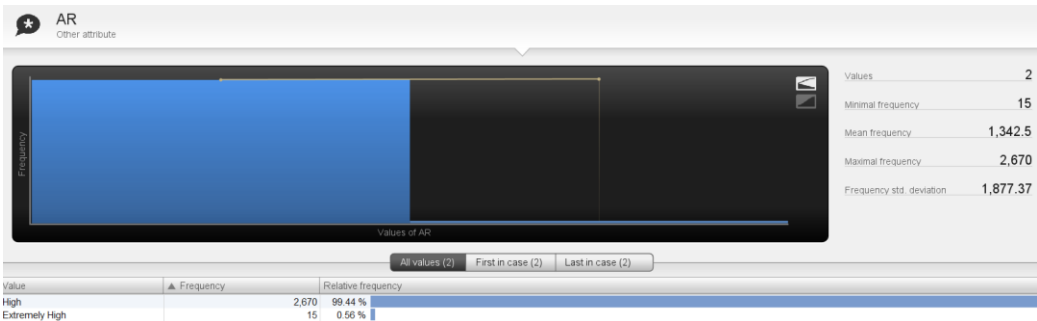


Fig. 5. A statistical overview of the allocation ratio

The production rate was also analyzed using the *attribute* filter to calculate the number of cases with low or medium **utilization efficiency**. The results showed that 36% of cases, i.e., 3624, had a low to medium utilization efficiency. Even though 90% of cases resulted in goods being stored, not all cases achieved optimal utilization efficiency. Hence, product storing might occur regardless of whether utilization efficiency is high or low.

The **throughput rate** analysis revealed that 2474 (24%) cases had low or medium production rates. On the other side, high **technical efficiency** was present in the majority of cases, 71% or 7199 instances. The mentioned results indicated a positive correlation between the production time and the busy time.

The **quality ratio** was also evaluated, showing that 11% of cases had a quality ratio between 30% and 60%. Fortunately, no cases with a quality ratio below 30% were detected.

The *attribute* filter in Disco was also used to calculate how many cases had a higher number of faulty products than initially planned, illustrating a higher **actual to planned scrap ratio**. A total of 5406 cases were extracted using this filter, i.e., 54% of cases, with the actual to planned scrap ratio above 60%. In some cases, the ratio even exceeded 100%. Therefore, the manufacturing company should perform root cause analysis to investigate the reasons for such results, monitor scrap rates and costs, and review equipment and other resources.

The results above demonstrate the relationship between the actual and planned number of faulty products. When exploring the ratio of faulty products to total produced quantity per unit time, no cases were detected with the **scrap ratio** above 60%.

When the *attribute* filter using Disco was applied to calculate the number of cases that have optimal performance indicators in terms of allocation ratio, utilization efficiency, throughput rate, technical efficiency, quality ratio, and scrap ratio, the authors reached the number of 38 cases whose every performance indicator was inside optimal levels. Fig. 4 illustrates a statistical overview of 38 cases recognized by Disco as having optimal KPIs, with a median case duration of 9.5 days.

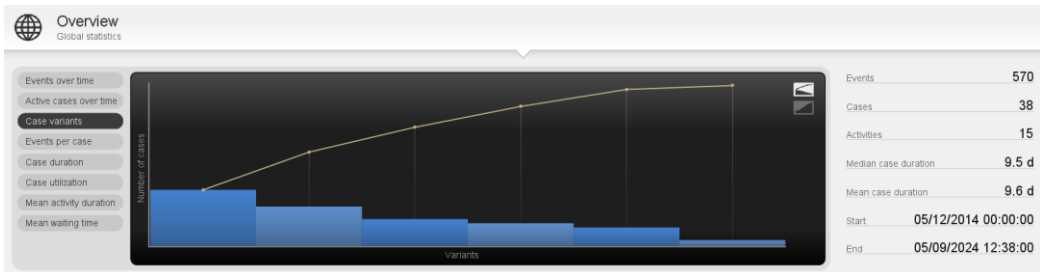


Fig. 6. Overview of cases with optimal performance indicators

Other performance indicators, such as **equipment load ratio** or **energy consumption**, can be studied using process mining techniques as well. Still, the existing event log lacks the information required for their calculation and should be subject to further adjustments.

C. Organizational perspective

Unlike Disco, ProM provides support for creating social networks as well [11]. Fig. 5 presents the social network generated in ProM using the *handover of work* metric. While nodes represent employees, arcs symbolize their mutual connections. Employees are ranked based on their impact on the production planning process,

whereas employees positioned in the centre of the network have the highest ranking. Hence, the employees in the manufacturing department, along with the manufacturing planner and technologist, are most significant for successful production planning.

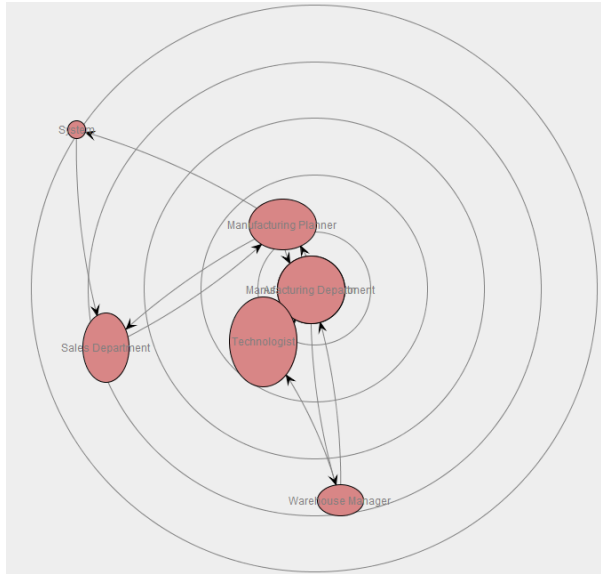


Fig. 7. Production planning social network

The common problem numerous companies encounter during production is resource overloading. To avoid such issues, the company should prioritize the most important tasks, assess resource capacities, and openly communicate with the employees. By investing time and effort in handling resource overloading, the company can improve productivity while reducing stress levels.

To achieve business excellence and improve customer satisfaction, the production planning process was thoroughly analyzed using PM tools – Disco and ProM. Such analysis provided valuable insights into the technical and organizational causes of production planning inefficiency, making it a promising method for further process optimization.

V. Conclusion and Future Work

Process mining techniques were used to discover and study the production planning process map, including frequency, performance, and organizational mining. Frequency perspective analysis indicated essential tasks for successful production planning, such as material requisition and product assembling. The performance view of the production planning process revealed numerous activities with long waiting times, along with three process bottlenecks. Since such issues

come with a high risk of decreasing efficiency and productivity, process mining is recognized as a method for their timely revealing. The paper also examined the handover of work, which provided insights into the key employees involved in process execution.

One of the key contributions of this paper is a KPI analysis relating to the production planning process, during which numerous performance indicators were analyzed using process mining tools. The research proved that more than half of the cases had low to medium performances, with the actual to planned scrap ratio being particularly critical. To overcome these problems, the company should perform root cause analyses and implement modern ICTs to automatically detect and monitor performance degradation. Additionally, identifying process bottlenecks can highlight specific parts of the production planning that can be subject to optimization.

Whilst previous research focused on automating the production planning processes, this research aimed to investigate how BPM and PM techniques can help companies analyze their business processes and perform KPI analysis. Combined application of Disco and ProM provided insights into frequency, performance, organization, and KPI perspectives of the production planning. As a result, this paper contributes to a better understanding of such processes, including challenges they may encounter. However, the event log used during this research was synthetically generated using Python. For that reason, access to real-time event logs could provide even more insights into process execution. The integration of BPM and PM in a real manufacturing company, whose event logs are automatically generated and stored by PAIS, represents a potential future work and the continuation of this research.

The combined application of BPM and process mining tools, such as Bonita, Disco, and ProM, presents a modern solution to frequent issues in the manufacturing industry, especially in the domain of production planning business processes. Process mining can enhance the BPM lifestyle by enabling process redesign, which leads to a more adaptive and dynamic environment [17]. Their successful integration can bring significant benefits for manufacturing companies and their customers, including process automation and digitization, reduction of long waiting times, resource optimization, etc. Introducing such changes can then help manufacturing companies improve their competitiveness in the business market.

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IMPLEMENTING ARTIFICIAL INTELLIGENCE TO REDUCE RISKS IN AUTO REPAIR SERVICES

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Abstract

Auto repair workshops are high-risk environments where workers face frequent accidents caused by slips, trips, heavy lifting, exposure to hazardous substances, and malfunctioning equipment. Despite advances in occupational health and safety (OHS) regulations, accident rates in Romania and across the European Union remain above average, highlighting the need for new preventive strategies. This paper explores how artificial intelligence (AI) can be systematically applied to reduce operational and safety risks in auto repair shops. Accident statistics and a detailed risk assessment of slips, trips, and falls provide the foundation for analyzing AI-based solutions, including computer vision, augmented reality, smart floors, voice assistance, and predictive analytics. A six-month pilot project conducted in a Romanian auto repair shop demonstrated a 28% reduction in minor accidents, faster hazard detection, and measurable economic benefits, while also revealing challenges such as false positives, resistance to change, and maintenance requirements. The findings confirm that AI can move workplace safety from reactive to preventive management by enabling real-time monitoring, proactive alerts, and predictive forecasting. The study concludes that AI, when combined with training and organizational adaptation, can significantly enhance worker protection, operational efficiency, and sustainability in the automotive repair sector.

Keywords

Occupational health and safety; reducing risks in car service; artificial intelligence; auto repair shop.

I. Introduction

Auto repair workshops are complex environments where safety and efficiency are fundamental for both operational success and compliance with labor regulations. Modern equipment such as car lifts, tyre changers, and wheel balancers contribute to productivity but also introduce risks of accidents if not properly used [1,2]. Despite improvements in occupational health and safety (OHS) regulations across Europe, auto repair shops remain high-risk workplaces. Activities involve manual handling of heavy components, working under elevated vehicles, and exposure to hazardous substances. Reducing workplace accidents is therefore a strategic priority.

While Artificial Intelligence (AI) has been widely studied in manufacturing and smart mobility, its applications in auto repair shops remain underexplored. Existing research often highlights AI's potential in diagnostics and predictive maintenance, but little attention is paid to its role in reducing workplace risk. This paper addresses that gap by analyzing how AI can help prevent accidents, detect hazards in real time, and improve overall safety culture. This study aims to explore how AI technologies can be systematically applied to reduce operational and safety risks in auto repair shops. The study is structured as follows.

Section 2 provides a statistical overview of workplace accidents in auto repair services, with particular attention to the most frequent and severe risks. A detailed risk assessment of slips, trips, and falls is included to illustrate the challenges mechanics face in everyday tasks.

Section 3 presents the core contribution of this study by discussing how AI-based solutions can address these risks. It describes specific technologies such as computer vision, smart floors, and predictive analytics, and includes a summary table that links each tool to the corresponding hazard it mitigates. To strengthen the practical dimension, the section also introduces a pilot case study demonstrating AI implementation in a Romanian auto repair shop.

Section 4 shifts the focus to the challenges and limitations of adopting AI, including financial, organizational, and ethical barriers that may hinder large-scale implementation. Finally, Section 5 concludes the paper by synthesizing the main findings, highlighting practical recommendations for the industry, and suggesting directions for future research and adoption.

II. Workplace accident statistics in auto repair shops

Workplace accidents are a key indicator of a country's occupational health and safety. Analysing these incidents provides a clear picture of the effectiveness of preventive measures, the level of worker training, and the organizational safety culture. In Romania, as in other European Union member states, reducing

workplace accidents has become a strategic priority, especially in high-risk sectors such as construction, manufacturing, and auto repair services. According to Eurostat (2023), Romania recorded an incidence rate of 2,050 accidents per 100,000 workers, higher than the EU average of 1,676 per 100,000 workers [5]. At the European level, more than 3.1 million non-fatal accidents were reported in 2021, with mechanical repair and maintenance consistently appearing among the high-risk subsectors [6]. However, differences between European countries remain significant, not only in accident frequency but also in severity and reporting practices.

The purpose of this analysis is to identify vulnerabilities and best practices that can be adapted to improve workplace safety in Romania, align with European standards, and leverage AI to strengthen prevention [7]. From the analysis of specific activities carried out in auto repair workshops, the main causes of accidents can be summarized as follows:

- Slips, trips, and falls (SRS): EU-OSHA reports that SRS account for 20–25% of accidents in the automotive repair sector [8]. These occur on slippery floors, trailing cables, or in cluttered work environments.
- Improper lifting and support of vehicles: Fatal accidents are often linked to mechanics working under poorly supported vehicles [9].
- Manual handling of loads: Approximately 22–28% of reported incidents result from incorrect manual handling [10]. Overexertion from lifting heavy parts (engines, wheels, batteries) is strongly associated with musculoskeletal injuries.
- Impact from vehicles, tools, or falling objects: Roughly 15–18% of incidents are caused by being struck by moving vehicles, falling objects, or malfunctioning equipment [11].
- Fires and explosions: Incidents involving welding or work near fuel tanks account for a severe category of accidents [12].
- Exposure to hazardous substances: Long-term health issues such as occupational asthma and dermatitis remain a concern, with exposure risks linked to solvents, paint dust, and asbestos [13].
- Welding fumes: Poorly ventilated welding activities significantly increase the risk of chronic respiratory diseases [14].
- Lifting equipment failures: Accidents related to defective or poorly maintained jacks and lifts continue to represent a major hazard [15].

A comparison of the main factors causing workplace accidents in auto repair shops in Romania, Germany, France, and the UK, based on official data published in Sectoral Reports in 2024, is presented in Figure 1.

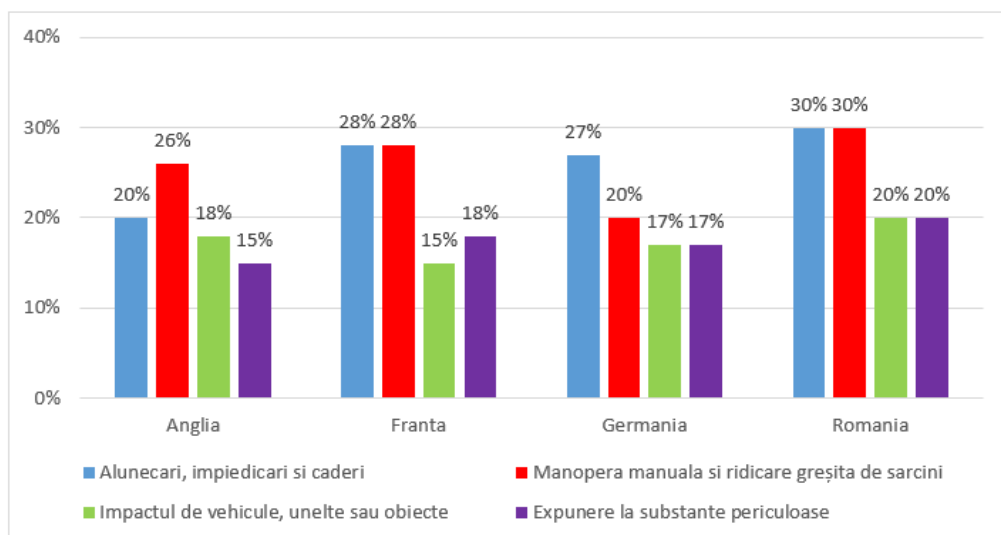


Fig. 1. Statistics of the Main Causes of Workplace Accidents in Auto Repair Shops (Source: European Sectoral Reports 2024)

Among the most frequent and dangerous risks encountered in an auto repair shop are slips, trips, and falls on the same level (SRS - Slip, Trip, and Fall). Although often underestimated, these risks represent a major cause of workplace accidents in the automotive sector [8,9]. Mechanical work frequently involves moving across slippery floors due to oil or fluid spills, handling tools in tight spaces, quick movements between work zones, and interaction with equipment or cables along the way. All these factors increase the likelihood of accidents caused by loss of balance or footing. Given the high incidence of this type of risk in auto workshops, it is very important that service units pay increased attention to identifying, assessing, and preventing these hazards. This can be achieved through the implementation of technical and organizational measures.

A risk assessment model for injuries and occupational illnesses associated with slipping, tripping, and loss of balance in the general mechanics section of auto repair shops is presented in Table 1, while the Action Plan based on the resulting risk level is detailed in Table 2.

During activities in an auto repair shop, especially in the general mechanics area, several common hazards have been identified that could cause significant workplace accidents. The risk assessment was conducted using the classical quantification method ($P \times S$), where P represents the probability of an event occurring, and S the severity of the possible consequences [10].

Table 1. SRS Risk Assessment in the Activity of the Auto Mechanics Department

No	Activity	Identified Hazard	Possible Event	(P)	(G)	(PxG)	Recommended measures
1	General auto mechanics	Engine area, lift	Slipping on fluids (oil, coolant)	4	4	16	Immediate cleaning, anti-slip flooring, fluid collection containers
2		Movement between workstations	Tripping over cables/tools, etc.	4	3	12	Organized workspace, marked pathways, cable/tool holders
3		Intervention under vehicle (lift/ramps)	Falling due to loss of balance	2	5	10	Posture training, good lighting, organized workspace
4		Parts washing area	Slipping on water/detergents/oils	4	4	12	Rubber mats, ventilation, wet area signage

Table 2. Action plan

Action Plan According to Risk Level		
Risk Level	Classification	Action Plan
R	High	Unacceptable risk. Work should not begin until the risk has been reduced.
M	Medium	Acceptable risk. Control measures must be introduced, efforts should be made to reduce the risk, and specific investments must be defined. Risk reduction measures must be implemented within one year.
S	Low	An improved preventive action is necessary, although periodic checks are required to ensure the effectiveness of the established control measures
B	Trivial	No specific action is required.

A major initial hazard identified is slipping in the engine area or near the lift, caused by the presence of technical fluids such as oil or coolant on the floor. The probability of this event was rated 4 (high), and the severity was 4 (accident with possible temporary work incapacity), resulting in a total risk score of 16 - considered high. Preventive measures include immediate spill cleanup, use of anti-slip flooring, and installation of fluid collection containers. Regarding movement between workstations, there is a constant risk of tripping caused by cables, tools, or other obstacles left in walkways. This risk was assessed with a probability of 4 and a severity of 3, resulting in a risk level of 12. Recommended measures include strict organization of the workspace, clearly marked access paths, and the use of dedicated holders for cables, hoses, and tools [11].

Another significant risk is associated with working under the vehicle, especially under ramps or lifts, where falls due to loss of balance may occur, particularly in poorly lit or cramped conditions. In this case, the probability was rated 2 (low), while the potential severity was rated at the maximum level of 5, resulting in a risk score of 10.

Measures required include training staff on proper working postures, ergonomic workspace organization, and ensuring adequate lighting in under-vehicle areas.

In the washing area, the main risk is slipping on water, detergents, or oily residues, especially when ventilation is ineffective. This risk was rated 4 for probability and 3 for severity, resulting in a risk level of 12. Recommended measures include installing anti-slip rubber mats, ensuring proper ventilation for quick drying of wet surfaces, and clearly marking slippery zones.

In conclusion, slip, trip, and fall risks in auto mechanics activities are constantly present and can lead to medium to high severity accidents. The consistent application of preventive measures plays a crucial role in reducing these risks and ensuring a safe working environment for personnel in auto repair workshops.

III. Implementing AI to reduce identified risks

Artificial intelligence offers a diverse set of approaches for addressing workplace risks in auto repair environments. Each technology contributes to prevention and mitigation in a specific way.

One of the most effective solutions is computer vision, which uses smart cameras equipped with AI algorithms to continuously monitor the workshop. Programs such as YOLOv8, a real-time object detection algorithm, and OpenCV, an open-source image processing library, enable these cameras to identify hazards including oil spills, misplaced tools, obstructed pathways, or even risky employee behavior such as rushing through crowded spaces. In simple terms, computer vision “teaches” cameras to recognize danger instantly. Once a hazard is detected, the system can trigger visual or audio alerts, allowing staff to respond before accidents occur [12].

Another promising technology is augmented reality (AR), which assists mechanics during complex repairs. By using tablets or smart glasses, employees can see overlays of instructions, wiring diagrams, or hidden vehicle components directly on their field of view. This approach reduces cognitive load on workers, helps prevent errors, and can decrease the time required for complex tasks by an estimated 10-15% [13]. Although early studies suggest significant benefits, more pilot data are required to confirm the reliability of these improvements across different workshop environments.

Smart floors represent a less conventional but highly effective innovation. These are workshop floors embedded with pressure, vibration, and liquid sensors. The system can immediately detect a fluid spill, sudden pressure changes, or the vibration caused by a fall.

Once triggered, the AI platform sends out audio-visual alerts and logs the event for later analysis. Beyond accident prevention, smart floors also serve as valuable

tools for continuous monitoring, ensuring that hazardous conditions are documented and addressed promptly.

Another area where AI is transforming safety is voice assistance. Using natural language processing (NLP) and automatic speech recognition (ASR) technologies, such as Whisper or GPT-based platforms, AI voice assistants can provide real-time spoken warnings. For instance, when the system detects an oil spill, it might announce: "Warning: fluid detected in Zone X. Please clean the area before continuing work." This proactive communication fosters a stronger safety culture by engaging workers immediately and directly in the prevention process.

Finally, predictive analytics plays a crucial role in anticipating accidents before they occur. By processing large datasets from past incident reports, video records, and sensor inputs, machine learning platforms such as PyTorch or MLFlow can identify behavioral patterns and environmental conditions that often precede accidents. For example, repeated observations of mechanics carrying heavy tools through cluttered spaces may indicate a higher probability of tripping incidents. Predictive models can issue preemptive alerts, enabling supervisors to intervene and reorganize the workspace before a risk materializes. Together, these AI applications demonstrate that risk reduction in auto repair shops can move beyond traditional reactive measures. By combining real-time detection, proactive communication, and predictive forecasting, AI transforms safety management into a preventive and adaptive system that continuously evolves with the work environment (table 3).

Table 3. Action plan

AI Tool / Technology	Function in Auto Repair Shops	Risk Addressed
Computer vision (YOLOv8, OpenCV)	Detect spills, clutter, unsafe behaviors	Slips, trips, poor workspace organization
Smart floors with sensors	Detect spills, falls, sudden vibrations	Slips, falls, equipment failure
Augmented reality devices	Display instructions, diagrams, and tutorials in real time	Human error, repair delays
AI voice assistants (NLP)	Provide real-time spoken safety alerts	Lack of awareness, delayed response
Predictive analytics (MLFlow, PyTorch)	Forecast risks using historical data	Accident anticipation, preventive alerts

A. Case Study: Pilot AI Implementation in a Romanian Auto Repair Shop

To test the applicability of AI-based safety solutions, a six-month pilot project was conducted in 2024 at a medium-sized auto repair workshop in Cluj-Napoca, Romania. The workshop employs 25 mechanics and handles approximately 1,200 vehicle repairs per month, ranging from general maintenance to complex diagnostics.

Objectives. The pilot aimed to evaluate whether computer vision and AI-based monitoring could: detect slips, trips, and falls (SRS) hazards in real time; reduce the number of recorded minor accidents; improve employee awareness of workplace risks.

Implementation. The project introduced a computer vision system consisting of five smart cameras installed in high-risk areas: the vehicle lift zone, parts washing station, and tool storage corridors. The system used YOLOv8 and OpenCV algorithms for object and spill detection, integrated with a voice assistant that issued real-time warnings through overhead speakers. For example: “Warning: oil detected near lift three.”

To ensure rapid responses, the system was connected to a central dashboard accessible by the shift supervisor, where alerts and incident logs were displayed. The project also included short training sessions for employees to familiarize them with AI alerts and reporting procedures.

Results. After six months, the following outcomes were documented:

- Reduction in incidents: Minor slip and trip accidents decreased by 28% compared to the same period in 2023.
- Faster hazard response: The average time between hazard occurrence (oil spill, misplaced tool) and corrective action decreased from 15 minutes to under 2 minutes.
- Employee feedback: A post-project survey showed that 72% of mechanics felt the system increased their situational awareness, while 18% initially found the alerts intrusive or distracting. With time, acceptance levels improved.
- Economic benefits: The workshop estimated annual savings of approximately €18,000, attributed to fewer accidents, reduced downtime, and lower insurance premiums.

Challenges. The pilot revealed important challenges:

- False positives because about 12% of alerts were unnecessary (e.g., detecting shadows as spills), which occasionally frustrated workers.
- Resistance to change as senior mechanics were initially sceptical, fearing surveillance or over-automation. Management addressed this by emphasizing the safety support role of the system.
- Maintenance needs because cameras require regular cleaning due to dust and oil, highlighting the importance of practical upkeep.

Lessons Learned. The pilot demonstrated that AI-based monitoring can significantly improve safety outcomes in auto repair shops, particularly in slip-and-trip prevention. Successful implementation requires:

- Strong communication to reassure staff that AI is a safety tool, not surveillance.
- Implementation in phases, starting with high-risk zones.
- Regular calibration and maintenance of equipment to minimize false alarms.

The management of the Cluj workshop concluded that the system was cost-effective and plans to extend it to two additional branches. The case study illustrates how AI can move from theory to practice, bridging the gap between digital innovation and occupational safety.

IV. Implementation challenges and limitations

Although the adoption of artificial intelligence in auto repair shops is beneficial for workplace safety and operational efficiency, several challenges and limitations may limit large-scale implementation. Understanding these barriers is essential to ensure that AI complements rather than complicates daily workshop operations.

High costs. The installation of smart cameras, augmented reality (AR) devices, or sensor-embedded floors requires significant upfront investment. In small and medium-sized enterprises (SMEs), which represent the majority of auto repair shops, financial constraints often prevent large-scale digital transformation. The cost is not limited to hardware acquisition. Ongoing expenses include software updates, system maintenance, and potential cloud-storage services for data retention. Mitigation strategies include phased adoption, starting with high-risk zones, and leveraging government or EU-funded digital innovation grants.

Training needs. Successful integration of AI systems depends on the workforce's ability to understand and operate these tools. Mechanics must not only follow safety protocols but also adapt to AI-enabled monitoring, dashboards, or AR-guided repair instructions. Research shows that insufficient digital literacy is a critical barrier to Industry 4.0 adoption in high-risk industries. Structured training programs, refresher courses, and human-centered interface design can minimize confusion and increase acceptance.

Resistance to change. The traditional culture of auto repair workshops, often built on hands-on experience and practical expertise, may slow acceptance of AI systems. Workers may view monitoring technologies as intrusive or as a threat to their autonomy. Pilot studies have shown that staff resistance can decrease significantly when AI is presented as a safety support tool rather than a surveillance system. Transparent communication, participatory design, and involving mechanics in the selection and testing phases can help reduce scepticism.

Data privacy and ethics. AI-enabled video monitoring and behavioral analysis raise legitimate concerns regarding surveillance, consent, and personal data protection.

In the European Union, compliance with the General Data Protection Regulation (GDPR) is mandatory when collecting and processing employee data. Beyond legal requirements, ethical implementation requires anonymization, limiting data retention, and ensuring that AI monitoring is strictly tied to safety objectives rather than performance evaluation.

Technical reliability. Like all technologies, AI systems are prone to errors, such as false positives (identifying risks that are not present) and false negatives (failing to detect actual hazards). In the Cluj pilot project, for example, approximately 12% of alerts were unnecessary, occasionally frustrating workers. This challenge is well documented in occupational AI applications, where environmental complexity can lead to inconsistent detection accuracy. To mitigate this issue, AI should be deployed alongside human oversight, with regular calibration and iterative system improvement based on real-world feedback.

While AI solutions offer opportunities to improve safety in auto repair shops, their implementation must be approached strategically. A combination of phased deployment, workforce training, participatory communication, and strict adherence to privacy regulations can significantly increase the likelihood of success. AI should be framed not as a replacement for human judgment but as a supportive tool that enhances worker protection, efficiency, and long-term sustainability.

V. Conclusions

This study examined how artificial intelligence can be systematically applied to reduce occupational risks in auto repair workshops, which remain among the most hazardous workplaces in Europe despite regulatory improvements. Statistical analysis revealed persistent vulnerabilities, particularly slips, trips, falls, manual handling injuries, and exposure to hazardous substances, that continue to impact mechanics' health and workshop efficiency.

By mapping these risks to specific AI-enabled technologies, the paper demonstrated that computer vision, augmented reality, smart floors, voice assistance, and predictive analytics provide complementary approaches for hazard detection, risk forecasting, and real-time intervention. The pilot project conducted at a Romanian auto repair shop confirmed the practical value of these tools: a 28% reduction in minor accidents, faster hazard response times, improved worker awareness, and measurable economic savings. At the same time, the case study highlighted challenges such as false alerts, resistance to change, and system maintenance, showing that technology alone is not sufficient without organizational adaptation.

Implementation challenges, including high costs, training needs, cultural barriers, privacy concerns, and technical reliability, underscore the importance of careful planning and phased deployment. For successful adoption, AI systems must

be introduced gradually, accompanied by clear communication, workforce training, and strict adherence to ethical and legal standards such as GDPR.

In conclusion, AI has significant potential to transform occupational safety in auto repair shops by moving from reactive accident response to proactive risk prevention. However, the path forward requires a balanced strategy that combines digital innovation with human oversight, continuous training, and organizational trust. Future research should expand pilot projects to multi-site and cross-country comparisons, integrate AI with virtual reality training modules, and develop cost-benefit models that support adoption in small and medium-sized enterprises.

If implemented responsibly, AI can contribute not only to safer workshops but also to a stronger safety culture and sustainable operational performance in the automotive service industry.

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CONTEMPORARY APPROACHES TO PROJECT MANAGEMENT

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Abstract

The JUSTEM project, funded under the LIFE Programme, addresses the challenge of supporting a just energy transition in coal-dependent European regions. An innovative feature of the project is the integration of the High-Level Structure (HLS) methodology, derived from ISO management standards, as a framework for planning, implementing, and evaluating the exploitation of results. This paper examines how the HLS framework has been applied to enhance the sustainability, scalability, and replication of JUSTEM's tools and outcomes. By mapping project deliverables against HLS principles, the study highlights the effectiveness of this structured approach in real regional transition contexts, with particular emphasis on addressing energy poverty.

Keywords

High-Level Structure (HLS); project management; just transition; JUSTEM project; results exploitation.

I. Introduction

In project management, experience gained from implementation contributes to enriching and transferring valuable knowledge and practices.

Transition is a major structural change that economically, technologically, environmentally, and socially impacts the entire community of a region. Energy poverty represents a major barrier to achieving fair energy transitions in Europe's post-carbon regions. The JUSTEM project addresses this challenge by strengthening regional capacities and engaging citizens in transition planning. Within project management, exploitation together with communication, dissemination, and

replication are key activities for transferring results, accumulated good practices, and the necessary steps for a successful transition. The introduction of the HLS approach for structuring and leveraging the JUSTEM project's results is a pioneering initiative in project management, offering a coherent, systematic methodology.

This paper aims to highlight two emerging trends in project management: results exploitation and the application of HLS, with illustrations from the JUSTEM project.

II. Literature Review

The concept of a “just transition” refers to the process of socio-economic transformation towards a low-carbon economy in a fair and inclusive manner for all social actors, particularly for workers, communities, and regions dependent on polluting industries. The term was popularised by trade unions in North America in the 1990s [1], and was later adopted by international organisations such as the International Labour Organization (ILO) – which published the “Guidelines for a Just Transition towards Environmentally Sustainable Economies and Societies” (2015) [2] – and the European Commission, which introduced the Just Transition Mechanism in 2020 as part of the European Green Deal [3].

The four pillars of the just transition concept [2], [4], represented in Figure 1, include social equity – protecting those affected by the transition, democratic participation – involving local communities and social partners, economic support – professional retraining and investments in new industries, and sustainable regional development – especially in mono-industrial regions (e.g., Jiu Valley, Ruhr, Silesia).

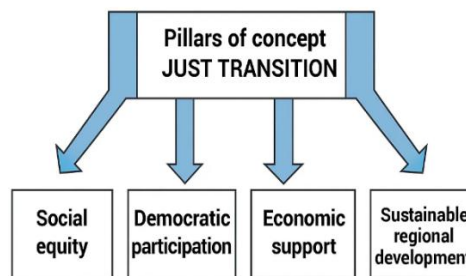


Fig. 1. Pillars of the Just Transition concept

In general, the dimensions analysed in transition research include public policies, through the design of compensatory measures and professional training programmes; multi-level governance, highlighting the roles of central, regional, and local authorities; stakeholder perceptions, explored through case studies assessing the social acceptability of transition; and impact indicators, referring to job quality, inequality reduction, and social cohesion. The literature highlights the complexity

of transition governance, and authors such as Healy and Barry (2017) [5] stress the importance of participatory planning and social equity, distributive conflicts, and intergenerational fairness, while the EU's Just Transition Mechanism operationalises these principles. Case studies (e.g., Ruhr, Jiu Valley) analyse how transition strategies can only be accepted if they provide real alternatives and local support [6].

The High-Level Structure (HLS) is a standardised architecture introduced by the International Organization for Standardization (ISO) to provide a common framework for structuring management system standards (e.g., ISO 9001, ISO 14001, ISO 45001). HLS was first published in Annex SL of the ISO/IEC Directives Part 1 (2012) and is intended to ensure coherence, compatibility, and interoperability across different management systems. This approach standardised terminology, chapters, and requirements, facilitating systems integration [7].

HLS establishes a common structure developed into 10 standardised chapters/clauses, enabling organisations to build an Integrated Management System (IMS), reducing redundancies and increasing operational efficiency [8]. The clauses cover context, leadership, planning, support, operations, performance evaluation, and improvement. The BSI Group (2015) [9] presents HLS as a model for coherence and cross-sectoral integration.

This approach is particularly useful in complex contexts, such as the ecological transition, where multiple standards are required – e.g., ISO 14001 for environment [10] and ISO 45001 for occupational health and safety [11].

HLS is relevant both in research and practice, being applied in the fields of sustainability, energy transition, and organisational governance, as it enables: the harmonisation of processes across different management standards, greater efficiency in policy implementation, and the alignment of environmental, social, and economic strategies with organisational objectives.

An example of an application of just transition is a management system based on HLS that integrates standards for the environment (ISO 14001), occupational health and safety (ISO 45001), and social responsibility (ISO 26000) [12], thus facilitating a systemic, planned transition towards sustainability.

HLS is frequently used as a foundation for the coherent implementation of ESG strategies (environmental, social, governance), enabling improved traceability and impact reporting [13].

A just transition can be supported by management standards and systems structured according to HLS, particularly in: strategic planning (Clause 6), leadership and engagement (Clause 5), impact assessment (Clause 9), and continuous process improvement (Clause 10).

Exploitation of results involves the use and valorisation of outcomes by third parties or in new contexts. The Horizon Results Booster guidelines (2021) [14]

emphasise that effective exploitation requires clarity, adaptability, and sustainability.

Although HLS is primarily applied in the corporate environment, its adaptation in European projects is relatively recent. JUSTEM is among the first examples of using this structure within a results exploitation framework for energy transition.

III. Exploitation Plan Using High-Level Structure

A. Overview of the exploitation plan development using High-Level Structure

In project management, an exploitation plan is considered well-made following the same logic of HLS, i.e. exploitation of results involves clear organization, strategic planning, measurement of the impact of needs and continuous improvement and aims to integrate the results into other organizations or policies.

Applying the HLS structure in the exploitation of the results of a European project offers a logical and transparent methodology, easy to integrate into public institutions or organizations already working with ISO standards. Within JUSTEM, HLS allowed structuring the process of valorizing the results in an exploitable, replicable and sustainable way.

Thus, exploitation was structured in three HLS stages:

- Definition: identification of the regional context, stakeholders, risks and objectives;
- Implementation: use of the Framework for Energy Poverty Assessment (FEPA), the Participatory Framework and Research Toolkit (PFRT), the Energy Poverty Alleviation Plans (EPAPs), and organization of participatory workshops;
- Improvement: performance evaluation through KPIs, feedback, and adjustments for replication.

The JUSTEM project exploitation plan introduces elements of the HLS logic, and as an element of know-how designed for HLS, it adapts the international ISO management standards. HLS is a common structure, which ensures coherence, compatibility, and integration between the project components and with fixed sections: organizational context, leadership, and planning.

Considering the three stages in which an HLS is developed and the distribution of the corresponding ISO clauses within the system, the actions for exploiting the JUSTEM project results are described in Table 1.

The developed concept of the HLS Operation Plan for the JUSTEM project is presented in Figure 2.

The benefits of the HLS Exploitation Plan for the JUSTEM project are a logical, clear structure that is easy to understand by external parties (e.g. funders, auditors); increased chances that the results will be taken up by organizations that already use

ISO standards; and easy integration of exploitation into existing organizational policies and demonstrates long-term thinking.

Table 1. Exploitation Mapping with ISO Clauses and HLS Stages of JUSTEM project

Stage (HLS)	ISO Clause (Annex SL)	Exploitation Actions
1. Define	Clause 4: Context of the organization – Understand internal and external issues, identify stakeholders, and define the scope of the system.	Understand the needs of regions for energy transition and energy poverty alleviation; define key stakeholders and goals for exploitation.
	Clause 5: Leadership – Ensure leadership commitment, define roles, responsibilities, and leadership-driven policies.	Leadership engagement at all project levels to commit to participatory transition planning and energy poverty alleviation strategies.
	Clause 6: Planning – Address risks and opportunities, set objectives, and define actions to achieve intended outcomes.	Set exploitation objectives; plan regional implementation strategies (Energy Poverty Framework, Impact Matrix, Alleviation Plans).
	Clause 7: Support – Identify resources, develop competence, ensure awareness, communication, and control of documented information.	Identify resources (research toolset, participatory methods, peer-to-peer learning concepts) needed to support exploitation efforts.
2. Implement	Clause 7: Support (continued) – Ongoing communication and competence development during implementation.	Expand support through communication platforms (JTP, workshops, participatory engagement methods).
	Clause 8: Operation – Plan, implement, and control operational processes to meet requirements.	Implement citizen participation tools, project pipeline development, and policy recommendation applications.

	Clause 5: Leadership (reinforced) – Maintain leadership commitment throughout project execution.	Ensure continuous leadership support during implementation activities to guarantee political backing and integration.
3. Improve	Clause 9: Performance evaluation – Monitor, measure, analyze, and evaluate performance through audits and reviews.	Monitor the effectiveness of Energy Poverty Plans, impact matrix usage, and citizen engagement frameworks.
	Clause 10: Improvement – Manage nonconformities, take corrective action, and foster continual improvement.	Implement corrective actions and adjust strategies based on replication feedback and exploitation performance.
	Clause 6: Planning (feedback loop) – Reassess risks and opportunities based on evaluation and new information.	Update exploitation strategies based on monitoring results, lessons learned, and stakeholder feedback.

Sources: [15], adapted after: Bsigroup, A High-Level Structure (HLS), <https://www.bsigroup.com/localfiles/nl-nl/iso-9001/bsi-annex-sl-whitepaper.pdf>

B. Example of the proposed framework – an overview of the impact on Jiu Valley

As presented in the previous section, the exploitation plan developed in the JUSTEM project clearly benefited from applying the principles of HLS. All the consortium partners contributed to identifying key exploitation alternatives for JUSTEM's main outcomes. Among the most valuable outputs are a framework for assessing energy poverty, a participatory framework and research toolset, the impact matrix for energy efficiency and renewable projects, and the Energy Poverty Alleviation Plans, which set an example on how the just transition can be approached based on local needs and particularities.

The Jiu Valley, one of the most challenged areas because of the coal mining phase out, serves as a case study to prove the relevance of the HLS methodology. Thus, the Jiu Valley currently has an Energy Poverty Alleviation Plan that was confirmed with relevant local and regional stakeholders and authorities, and several projects were identified for further funding. The projects include energy efficiency upgrades for households and public schools, training programs for green jobs, and the

valorization of tailings to regenerate the environment and create new economic and social opportunities.

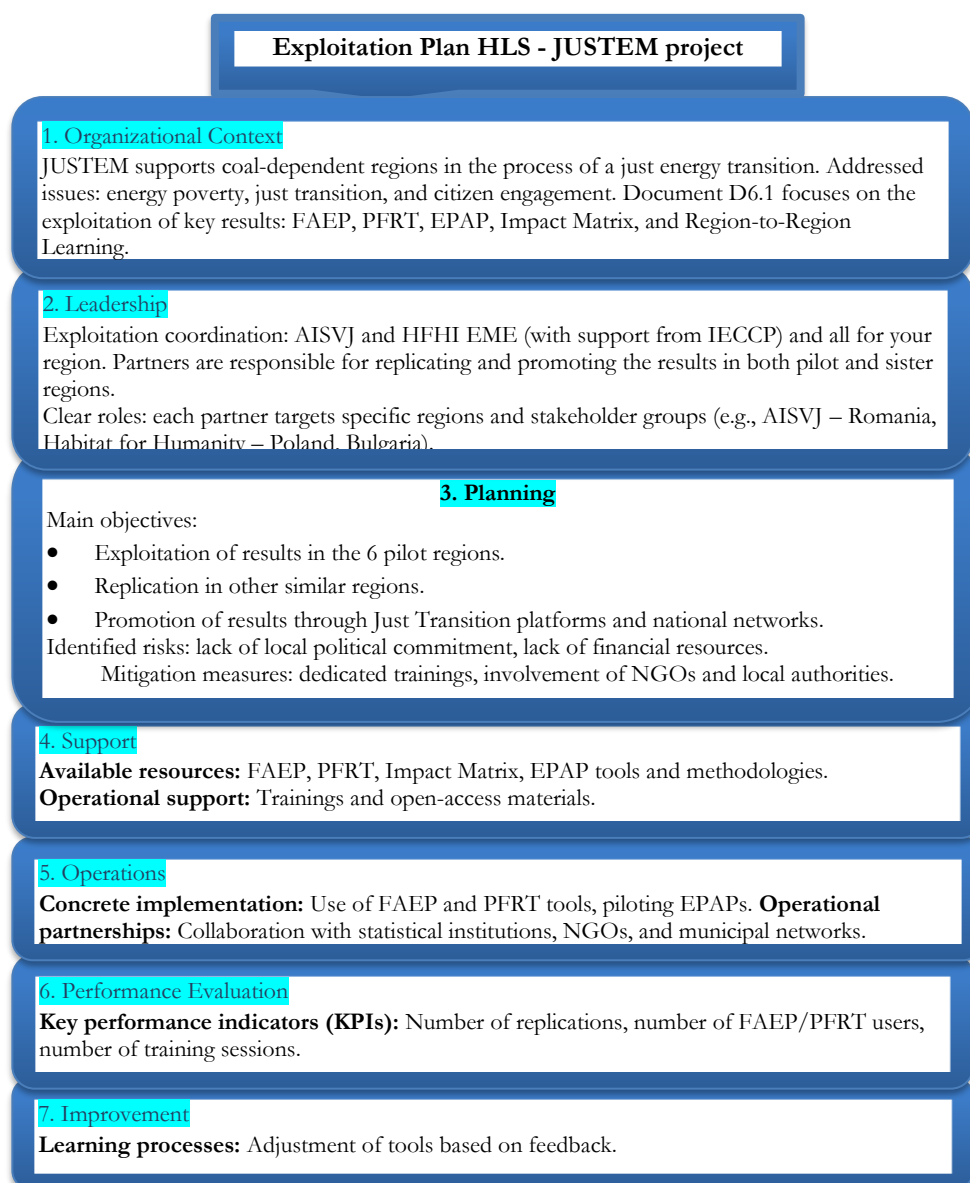


Fig. 2. Exploitation Plan HLS JUSTEM project

By reaching out to the identified stakeholders, the data collected through the implementation of the JUSTEM deliverables sets the ground for fast and efficient writing and submission for funding for the above-mentioned projects. The estimated impact of these projects (which are part of the exploitation plan) is aimed

at reducing the main social and demographic challenges that currently put Jiu Valley in a very difficult economic situation.

Another important aspect is the potential of Jiu Valley to set a positive example for other regions in Romania that are impacted by the coal mining phase out and that are targeted by the just transition, serving as a best practice for them.

IV. Conclusions

In conclusion, the exploitation plan, when applied in line with the HLS principles, leads to the valorisation of the project results. It must identify, plan, implement, monitor, and improve the use of the results – exactly as HLS requires for any management system.

We find that JUSTEM's project management and implemented activities have laid a solid, practical foundation for addressing energy poverty and facilitating a just transition in Europe's coal-affected regions [16]. Through a coordinated effort combining data-driven tools, participatory frameworks, and strategic policy planning, the project has moved beyond theoretical discussions toward practical, region-specific applications. The suite of results—including FEPA, PFRT, EPAPs, the Impact Matrix and the Region-to-Region Learning Concept—offers not only independent value but also enormous synergistic potential when implemented in an integrated manner.

In the six pilot regions, the project has demonstrated that sustainable, inclusive, and replicable approaches are achievable. Local authorities, statistical agencies, NGOs, and civil society actors now have adapted methodologies, technical resources, and tested use cases that enable them to design responsive and forward-looking interventions. This locally grounded yet transnationally relevant approach is essential to ensuring that energy transition policies are environmentally sound, socially equitable, and economically viable. The project's emphasis on stakeholder engagement and co-creation ensures that affected communities are not passive recipients of policies, but active shapers of their own future. The participatory tools developed—particularly the APOLLO-Live platform—mark a shift toward democratic governance in the development of energy and climate strategies, enabling consensus-building, conflict resolution, and enhanced accountability. The pathways for exploitation and replication ensure that the project's impact will extend well beyond its initial timeframe and geography. Alignment with EU policy instruments such as the Just Transition Fund, the LIFE Programme, and the broader goal of the European Green Deal makes

JUSTEM's results highly suitable for integration into ongoing national and regional strategies. The project's legacy lies not only in the reports, tools, policies, and proposed projects it has produced, but also in the capacity it has built among stakeholders to continue innovating, collaborating, and expanding their impact. In

conclusion, JUSTEM serves as a compelling model for other regions navigating the complex landscape of decarbonisation, stabilisation, transition, and socio-economic restructuring.

This paper illustrates how systemic challenges such as energy poverty [17] can be addressed through inclusive design, rigorous evidence, and strategic alignment with European policy objectives. As coal-dependent regions in Europe and beyond face their transition trajectories, the methodologies and partnerships fostered by JUSTEM offer a powerful model to ensure that no community is left behind in the energy transition.

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FOLLOWING THE CODE: HOW ACADEMIC CODES OF CONDUCT HELP STUDENTS BECOME ETHICAL LEADERS IN BUSINESS

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Abstract

The connection between academic ethics codes and professional codes in business ethics is a critical area of study, particularly in the context of ethical decision-making and socially responsible behaviour. Academic ethics codes are designed to guide behaviour within educational institutions, while professional codes of conduct provide standards for ethical behavior in the workplace. Both play a significant role in shaping the ethical mindset of individuals, from students to professionals. This paper provides a synthesis of existing literature on the interplay between these codes, their influence on ethical decision-making, and their role in fostering socially responsible behavior.

Keywords

Academic ethics and integrity; business ethics; ethics code; business leaders; ethical conduct.

I. Introduction

Institutional culture is a critical determinant of academic ethics within European universities. Research indicates that the structural frameworks of universities, including funding, evaluation, and publication practices, can both support and undermine research integrity [1]. For instance, the pervasive competition in academic environments often leads to pressures that may compromise or put into question ethical standards. However, institutions can foster a culture of integrity by implementing supportive structures and promoting ethical practices.

A study examining the views of researchers, managers, and administrators in several European countries found that institutional systems, such as workload and research governance, significantly influence day-to-day work environments and, by

extension, research integrity [1]. This highlights the need for universities to create conditions that support ethical conduct, rather than simply relying on individual responsibility.

Moreover, developing a campus-wide ethos that encourages integrity is essential. This can be achieved through comprehensive academic integrity policies, campus-wide programs, and consistent communication of ethical standards [2]. Such efforts not only reduce academic dishonesty but also cultivate a moral culture that promotes ethical behavior among students and staff. The most important tool for implementing ethical behaviour is the code of ethics, which contains the desired ethical norms.

The academic literature reveals considerable variation in how ethical codes are defined and conceptualized. At the most basic level, codes of ethics are understood as formal documents that articulate professional values, standards, and behavioral expectations [3]. However, scholars have developed more nuanced definitional frameworks that capture the multifaceted nature of these instruments.

Codes of ethics are variously defined as "aspirational or prescriptive social contracts that organize professional values and practices" [4]. This definition highlights two critical dimensions that recur throughout the literature: the aspirational-prescriptive distinction and the social contract function of codes.

The present paper does not intend to comprise a quantitative study, only a theoretical synthesis of the topic. As such, we intend to point out the possible interconnection between the two types of ethics codes from the perspective of teaching academic ethics at a technical university to students who represent actual or future professionals in their fields.

II. The Impact of Teaching Practices on Academic Integrity

Teaching practices play a crucial role in promoting academic integrity. Ethical teaching involves more than just conveying knowledge; it requires educators to model integrity in their interactions with students and colleagues. From our more than five-year practice of teaching academic ethics and integrity, we have observed that effectively exemplifying ethical values and consistently promoting these norms and values is crucial. However, factors such as heavy workloads, lack of training, and the casualization of the academic workforce can hinder these efforts [5].

One effective approach to promoting academic integrity is through ethical teaching and assessment. Strategies such as authentic assessment, experiential learning, and program-level course design can encourage deep learning and reduce the likelihood of academic misconduct [6]. Additionally, ethical care and principles in teaching and assessment can foster a culture of integrity, benefiting both students and educators.

A. Academic Ethics Codes and Their Role in Ethical Development

Academic ethics codes are established by educational institutions to promote integrity, honesty, and responsible behavior among students and faculty. These codes often address issues such as academic integrity, respect for others, and the responsible use of resources. They serve as a foundation for ethical development, preparing students for the ethical challenges they will face in their professional lives.

Academic ethics codes typically include principles such as honesty, fairness, and accountability. For instance, many universities have honor codes that prohibit cheating, plagiarism, and other forms of academic dishonesty. These codes also often emphasize the importance of respecting diversity and promoting inclusivity within the academic community [7] [8].

B. The Impact of Academic Ethics Codes on Student Behavior

Ethics education is a vital component of academic integrity initiatives. Universities have increasingly incorporated ethics education into their curricula, particularly in response to high-profile ethical scandals in business and science [9]. This shift reflects a growing recognition of the importance of ethical training in preparing students for professional roles.

Research indicates that academic ethics codes can have a positive impact on student behavior. For example, studies have shown that students who attend institutions with strong honor codes are less likely to engage in unethical behavior, both in academic and professional settings [10] [11]. This suggests that academic ethics codes play a crucial role in shaping the ethical values of future professionals.

III. Professional Codes of Conduct and Their Role in Business Ethics

Professional codes of conduct are established by industries, organizations, or professional associations to guide ethical behavior in the workplace. These codes often address issues such as confidentiality, conflicts of interest, and the responsible use of resources. They are designed to promote ethical decision-making and ensure that professionals act in the best interests of their organizations and society.

Professional codes of conduct vary depending on the industry and organization, but they often include principles such as integrity, transparency, and accountability. For example, the accounting profession has a well-established code of ethics that emphasizes the importance of professional competence, due care, and confidentiality [12] [13].

Research has shown that professional codes of conduct can have a positive impact on employee behavior. For instance, studies have found that employees who work in organizations with strong ethics codes are less likely to engage in unethical

behavior, and they are more likely to make decisions that align with the organization's ethical standards [10] [14].

IV. The Connection Between Academic and Professional Codes

The connection between academic ethics codes and professional codes of conduct is lies in their shared goal of promoting ethical behavior in an organization. Academic ethics codes intend to lay the foundation for ethical decision-making during the formative years, while professional codes of conduct build on this foundation, providing guidance for professionals in the workplace.

Academic ethics codes intend to influence professional codes of conduct by shaping the ethical values and principles that students carry with them into their professional lives. For example, students who are exposed to strong academic ethics codes are more likely to understand the importance of ethical behavior in the workplace [15] [11]. However, further research into this topic is needed to confirm this thesis.

Professional codes of conduct also influence academic ethics codes by providing a framework for ethical education. Many academic institutions incorporate professional codes of conduct into their curriculum, ensuring that students are prepared to meet the ethical challenges they will face in their professional lives [16] [17]. In Romania, an example consists of the Education Law 199/2023, which codifies ethical norms pertaining to plagiarism and other forms of unethical conduct, such as harassment, sabotage and other forms also found in Romanian labour law.

A. The Role of Codes in Ethical Decision-Making

Ethical decision-making is a critical skill for both students and professionals. Academic ethics codes and professional codes of conduct play a crucial role in shaping this skill by providing a framework for ethical decision-making.

In an academic context, ethics codes provide students with the principles and values they need to make ethical decisions. For example, students who are guided by an academic honor code are more likely to make decisions that align with the principles of honesty and integrity [10] [11].

In professional settings, codes of conduct provide employees with the guidance they need to make ethical decisions. For instance, employees who are familiar with their organization's code of ethics are more likely to make decisions that align with the organization's ethical standards [14] [13].

B. The Role of Codes in Promoting Socially Responsible Behavior

Socially responsible behavior is a key component of both academic ethics codes and professional codes of conduct. These codes promote socially responsible behavior by encouraging individuals to consider the impact of their actions on society.

In academic settings, ethics codes promote socially responsible behavior by encouraging students to consider the impact of their actions on the academic community. For example, students who are guided by an academic honor code are more likely to engage in behaviors that promote social responsibility, such as volunteering and community service [15] [11].

In professional settings, codes of conduct promote socially responsible behavior by encouraging employees to consider the impact of their actions on society. For instance, employees who are familiar with their organization's code of ethics are more likely to engage in behaviors that promote social responsibility, such as environmental sustainability and community engagement [14] [13].

C. Challenges and Opportunities in Aligning Academic and Professional Codes

While there are many opportunities for aligning academic ethics codes and professional codes of conduct, there are also challenges. One of the key challenges is ensuring that academic ethics codes are aligned with the ethical standards of the professional world. This requires ongoing collaboration between academic institutions and professional organizations.

There are several opportunities for aligning academic ethics codes and professional codes of conduct. For example, academic institutions can incorporate professional codes of conduct into their curriculum, ensuring that students are prepared to meet the ethical challenges they will face in their professional lives. Additionally, professional organizations can work with academic institutions to develop ethics codes that align with the ethical standards of the professional world [16] [17].

One of the key challenges in aligning academic ethics codes and professional codes of conduct is ensuring that both codes are relevant and effective. This requires ongoing research and evaluation to ensure that the codes meet their intended goals. Additionally, differences between academic and professional ethical standards can create confusion for individuals transitioning from academic to professional settings [7] [8].

V. Discussion and outlook

As stated, this paper does not include an actual study to demonstrate, based on empirical data, the degree of influence and interconnection between academic and

professional codes of ethics. This is scope for further research, the methodology of which is still to be studied. The authors limit themselves to their experience of teaching academic ethics at a technical university. A future study will have to focus on all types of universities across more countries to demonstrate the assumed reciprocal influence of the two presented types of codes of ethics.

VI. Conclusion

The connection between academic ethics codes and professional codes of conduct is a critical area of study, particularly in the context of ethical decision-making and socially responsible behavior. Academic ethics codes lay the foundation for ethical decision-making, while professional codes of conduct build on this foundation, providing guidance for professionals in the workplace. Both codes play a crucial role in shaping the ethical mindset of individuals, from students to professionals.

By aligning academic ethics codes and professional codes of conduct, we can create a seamless transition from academic to professional settings, ensuring that individuals are prepared to meet the ethical challenges they will face in their professional lives. This alignment not only promotes ethical decision-making but also fosters socially responsible behavior, which is essential for creating a more ethical and responsible society.

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A FRAMEWORK FOR DIGITAL-SELF-LEARNING IN SOCIAL ENTREPRENEURSHIP FOR THE FUTURE OF COLLABORATION BETWEEN UNIVERSITY AND COMMUNITY

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Abstract

This paper introduces a strategic framework for digital self-learning in social entrepreneurship (SE) to enhance collaboration between universities and communities. Drawing on the DigiFunCollab Erasmus+ project (2023-1-IT02-KA220-HED-000158730, <https://digifuncollab.eu/>), it explores SE ecosystems in Romania, Slovenia, Germany, and Italy, highlighting the need for digital skills and flexible education models. The framework includes multilingual e-learning modules, mentoring programs, and policy recommendations. Higher education institutions play a pivotal role in fostering SE competencies and mindset. The study concludes with actionable strategies to strengthen SE ecosystems across Europe, emphasizing digital learning as a catalyst for inclusive, sustainable development and community engagement.

Keywords

Education/training; digital skills; self-learning; social entrepreneurship (SE); university third mission; university – community ecosystem.

I. Introduction

In the last years (because of the specifics of the post-pandemic period) universities worldwide have been focusing on developing their Triple Helix framework (centered on the dynamic interaction between universities, industry, and government) that serves as a foundational framework for fostering innovation and sustainable development. In the context of university–community collaboration, this model emphasizes the university’s evolving role beyond education and research, positioning it as a proactive agent in societal transformation. By engaging with local communities and public institutions, universities can co-create solutions to social challenges, promote entrepreneurial mindsets, and support inclusive growth. The synergy among the three helices enables the development of robust ecosystems where knowledge exchange, digital learning, and social entrepreneurship thrive, ultimately strengthening regional resilience and cohesion. Furthermore, the Triple Helix model plays a crucial role in advancing (SE) by fostering collaboration among universities, industry, and government to address societal challenges through innovation. In this context:

- Universities contribute research, education, and human capital development, nurturing entrepreneurial mindsets and social innovation skills;
- Industry offers practical insights, resources, and scalability for socially driven ventures;
- Government provides policy support, funding mechanisms, and regulatory frameworks that enable inclusive and sustainable entrepreneurship.

This tri-sectoral interaction creates a fertile ground for co-creation, where social entrepreneurs can emerge from academic environments and be supported by both public and private sectors. It strengthens community engagement, promotes digital learning, and builds resilient ecosystems for long-term social impact.

SE has emerged as a powerful approach to addressing complex societal challenges through innovative, market-based solutions that prioritize social impact alongside financial sustainability [1]. The impact of SE companies (as small businesses most of the time) is related to social sustainability aspects and supporting local communities, disadvantaged groups and individuals, combating poverty and creating opportunities [2-4]. Learning and self-learning in the field of SE are extremely complex, and most of the time training and mentoring programs are missing, the initiatives being generated by experienced entrepreneurs or enthusiastic young people who need consultancy. As a result, the need for training is real and urgent, and the need for digital skills to support such businesses is even greater [5-7] and can be supported by e-learning solutions [8,9].

This research examines the current state of SE in Romania, Slovenia, Germany and Italy by analysing key challenges and opportunities, and places special emphasis on the critical need for education in this field. Furthermore, the legal

frameworks and financial support systems in each country will be analysed, giving a deep understanding of the SE phenomenon. Furthermore, there will be a debate on the development of SE in Romania that has followed a unique trajectory shaped by the country's post-communist transition, European Union (EU) integration, and ongoing socioeconomic challenges. The situations of supporting SE education will be analysed and recommendations will be provided.

This study will demonstrate the necessity of modern (self-)education in SE, underling the usefulness of the digital skills development by and with the support of higher education institutions. This approach has been implemented in the context of the DigiFunCollab Erasmus+ project (implementing by an international partnership consist of partners from Romania, Slovenia, Germany and Italy) that demonstrates the active role universities could play in their communities and regions. Furthermore, the DigiFunCollab project exemplifies how higher education institutions (HEIs) can go beyond their traditional roles by actively engaging with local communities and public stakeholders to co-create solutions for societal challenges. Through student-led initiatives, mentoring programs, and digital self-learning modules, DigiFunCollab operationalizes the Triple Helix model by integrating academic knowledge, civic engagement, and policy support. This tri-sectoral synergy enables the development of over 50 social entrepreneurship projects across Romania, Slovenia, Italy, and Germany, addressing issues like youth empowerment, environmental sustainability, and cultural inclusion. The model ensures that universities act as knowledge facilitators and social change agents, while industry and government contribute resources, scalability, and regulatory frameworks to sustain impact.

The paper is structured as following: first part presents a comprehensive comparison study of SE in Romania, Slovenia, Germany, and Italy, analysing their legal frameworks and financial support systems; second part will describe the methodological framework proposed for the digital-self-learning courses in SE for the future of collaboration between university and community; the third part is dedicated to the DigiFunCollab case study presentation and debate, including the discussions of the project impact. Finally, some conclusions and recommendations will be included.

II. A comprehensive comparison study of social entrepreneurship in Romania, Slovenia, Germany, and Italy

A. Methodological aspects

SE plays a crucial role in addressing societal challenges across Europe. This study provides a comprehensive comparison of the legal and financial support landscapes for SE in four EU member states: Romania, Slovenia, Germany, and Italy. By

examining their distinct approaches to defining, recognizing, and funding social enterprises, this report aims to highlight best practices, identify gaps, and offer insights for policy development and cross-country learning.

The social economy sector, encompassing social enterprises, cooperatives, mutuals, and associations, contributes significantly to employment, social cohesion, and sustainable development. However, the specific conditions under which these entities operate vary considerably across different national contexts, influenced by historical, cultural, and political factors. Understanding these variations is essential for fostering an enabling environment for SE.

This analysis methodology includes several steps as follows:

1. Analysis of the legal frameworks based on an in-depth analysis of how each country legally defines and recognizes social enterprises;

2. The analysis of the financial support systems by a detailed examination of the public and private funding mechanisms available to social entrepreneurs, including the role of

EU-level programs;

3. The comparative analysis synthesis, which presents the findings, identifying similarities, differences, best practices, and existing gaps;

4. Conclusion and recommendations will be made after summarizing key takeaways and proposing actionable recommendations for enhancing the SE ecosystem in these countries and beyond.

This study draws on official government sources, EU publications, and relevant research to provide a robust foundation for its comparative analysis.

B. Comparison of the SE legal framework

Table 1 delves into the legal frameworks governing SE in Romania, Slovenia, Germany, and Italy. Each country has adopted a distinct approach to defining, recognizing, and integrating social enterprises within its national legal system, reflecting diverse policy priorities and historical developments [10-20].

Table 1. Summary of the legal frameworks on SE in the analysed countries

Feature	Romania	Slovenia	Germany	Italy
<i>Specific Legal Framework</i>	Yes (Law on Social Economy, 2015)	Yes (Social Entrepreneurship Act, 2011/2018)	No (National Strategy, 2023)	Yes (Law 381/1991, 2005-06, 2016-17 reforms)

<i>Definition of SE</i>	Yes (Law on Social Economy)	Yes (Social Entrepreneurship Act)	No (No official definition)	Yes (Various laws and reforms)
<i>Legal form of profession and competencies recognition</i>	Specific criteria for recognition	Status-based, not a distinct legal form	No specific legal form	Broad, including social cooperative and others
<i>Benefits and recognition</i>	Public Benefit status, reserved contracts	Free leases, set-aside, procurement, tax benefits, access to finance	Improved framework conditions, support programs	Legal recognition expanded activities, third sector integration
<i>Evolution and maturity</i>	Relatively recent, evolving	Evolving, status-based approach	Nascent, national strategy recently adopted	Well developed, decades of evolution

The analysis in Table 1 highlights the diverse approaches taken by the four countries. Regarding the formal recognition of the SE profession and competence, Italy and Romania have specific laws that define and recognize social enterprises. Italy's framework is particularly mature, having evolved over the course of decades. Slovenia provides a "social enterprise status" that confers benefits without requiring a distinct legal form. Germany, uniquely among the four, lacks a specific national legal framework, relying instead on a recently adopted national strategy and regional initiatives. From the perspective of SE evolution and maturity level, Italy's framework is the most developed, with a long history of legislative evolution from social cooperatives to a comprehensive third-sector reform. Romania and Slovenia have more recent, dedicated legislation. Germany is in the early stages of formalizing its support through a national strategy, indicating a less mature but developing legal landscape.

Regarding the scope and flexibility of SE, while all countries aim to support entities with social objectives, their methods vary. Romania's framework includes specific provisions for "social insertion enterprises". Slovenia's status-based approach offers flexibility. Italy's broad framework allows various legal entities to qualify. Germany's fragmented approach means that the scope and nature of support can differ significantly across regions.

Regarding integration with broader legal systems, Romania integrates the social economy into social assistance and cooperative laws. Italy has moved towards

integrating social enterprises within a comprehensive “third sector” reform, aiming for a unified approach. Slovenia's status provides specific benefits within existing legal structures. Germany's approach is more decentralized, with regional efforts attempting to fill the national gap.

As underlined by the study, the legal landscapes for SE in these four countries present a spectrum from highly formalized and evolved (Italy) to emerging and fragmented (Germany), with Romania and Slovenia occupying intermediate positions with dedicated but more recent legislation. These legal foundations significantly influence the operational environment and the availability of support for social enterprises in each nation.

C. Analysis of financial support systems

The examination of financial support systems available for SE covers both public and private funding sources, as well as the crucial role of EU-level programs that are accessible to all four countries [10-20] (Table 2). The EU-level funding programs available often complement or co-finance national and regional initiatives, providing a crucial layer of financial support and strategic direction across the EU.

Table 2. Comparative analysis of financial support systems

Feature	Romania	Slovenia	Germany	Italy
<i>Public funding sources</i>	Grant schemes (Start-Up Nation), subsidies, reserved contracts	European programs, Fund, Export and Development Bank, SEF	Development Regional authorities (EU funding, guarantees)	Regional National (Invitalia, fiscal incentives, guarantees), Regional measures
<i>Private funding sources</i>	Microfinance (Erste), Crowdfunding	Impact investment funds (FUND2740), Banking sector programs	Social banks, foundations, impact investors, crowdfunding, microdonations, grants	Traditional and social banks (Banca Etica), specialized banks, crowdfunding, microfinance
<i>EU funding access</i>	Yes (ESF+, InvestEU, ESIFs)	Yes (ESF+, InvestEU, ESIFs)	Yes (ESF+, InvestEU, ESIFs)	Yes (ESF+, InvestEU, ESIFs)

<i>Access challenges</i>	Significant, reliance on own funds	Moderate, dedicated funds available	Potential regional disparities	Generally good, diverse options
<i>Innovation in funding</i>	Limited	Moderate (private impact fund)	Moderate (active private sector)	High (specialized social banks, innovative instruments)
<i>Non-financial support</i>	Limited mention	Training, mentorship, networking, and co-working spaces	FASE (resources, advice)	Incubators (FabriQ), mentoring, support organizations

The European Social Fund Plus (ESF+) is a primary EU fund with a substantial budget of €142.7 billion for the period 2021-2027 [18]. Furthermore, the InvestEU Programme is designed to support sustainable and inclusive investments, innovation, and job creation across Europe [19]. A specific component, the InvestEU Microfinance and Social Entrepreneurship Guarantee, aims to bridge funding gaps for micro-borrowers, micro-enterprises, and social enterprises. It includes a dedicated Social Investment and Skills Window with a budget of €2.8 billion in EU guarantees, covering critical areas like education, training, skills development, microfinance, and broader social impact initiatives [20]. European Structural and Investment Funds (ESIFs) represent the EU's main financial instruments for promoting economic, social, and territorial cohesion across its regions [21]. ESIFs include the European Regional Development Fund (ERDF) and the ESF+ (formerly ESF). They are instrumental in investing in job creation, fostering sustainable economies, and supporting social development, with a primary objective of reducing economic and social disparities among EU regions [21].

The synthesis presented in Table 2 illustrates the varied financial landscapes:

- Public vs. private emphasis - While all countries utilize both public and private funding, Italy appears to have the most structured and extensive national public funding apparatus, complemented by a highly diverse private sector. Germany relies heavily on regional and private initiatives due to the lack of a national framework. Romania and Slovenia present a balanced mix, with Slovenia showing a strong reliance on EU programs and dedicated national funds like SEF.
- Access to funding - Romania faces the most significant challenges in funding access, with social enterprises often resorting to self-financing. Slovenia benefits from dedicated funds and a growing ecosystem of support organizations.

Germany's decentralized approach can lead to regional disparities in funding access. Italy's mature ecosystem provides a wide array of options, from traditional banking to innovative social finance instruments, generally indicating good access.

- **Role of EU Funds** - EU-level programs such as ESF+, InvestEU, and ESIFs are critical funding sources for SE across all four countries. They often complement or co-finance national and regional initiatives, serving as a unifying and significant source of support that transcends national specificities.
- **Innovation in funding** - Italy demonstrates a higher degree of innovation in private funding, with specialized social banks and impact investment vehicles. Slovenia also has a notable private impact investment fund. Germany's private sector is active in impact investing and crowdfunding. Romania's private funding is present but appears less diversified compared to Italy.
- **Non-financial support** - Slovenia and Italy show more explicit integration of nonfinancial support (training, mentorship, networking) alongside financial aid, which is crucial for the sustainable growth of social enterprises. Germany has organizations like FASE providing resources and advice, while Romania's non-financial support is less explicitly detailed in the available information.

In conclusion, the financial support systems for SE vary considerably across these four countries, influenced by their respective legal frameworks and economic contexts. EU funds play a vital role in providing a consistent layer of support, but national and regional specificities dictate the overall funding landscape and the ease of access for social enterprises.

D. Gaps and challenges for SE

Related to the legal framework gaps identified, the following aspects were considered important for future developments (synthesis of the previous work of [22-27]):

- The most significant legal gap is Germany's lack of a specific national legal framework for the social economy [3]. While the 2023 National Strategy is a positive step, the reliance on regional initiatives creates potential inconsistencies and unequal access to support and recognition across the country. This fragmentation can hinder the scaling of social enterprises and create legal ambiguities.
- A common challenge across all countries, though not explicitly detailed in their individual frameworks, is the limited mechanisms for cross-border recognition of social enterprise status. This can impede the expansion and collaboration of social enterprises across EU borders, creating administrative burdens and legal uncertainties for organizations operating internationally;
- While social impact is central to SE, the legal frameworks generally lack comprehensive and standardized requirements for impact measurement and

reporting. This gap can hinder accountability, limit the ability to demonstrate the value of social enterprises, and make it difficult for investors and policymakers to assess their effectiveness and allocate resources efficiently.

Related to the financial support gaps, the following aspects have been considered relevant for future developments:

- Romania faces significant gaps in funding accessibility, with a high proportion of social enterprises relying on their own funds for growth [5]. This suggests either insufficient availability of external financing or significant barriers (e.g., complex application processes, lack of awareness, stringent eligibility criteria) that prevent social enterprises from accessing existing public and private programs. This limits their growth potential and sustainability.
- While Germany benefits from strong private sector involvement, the decentralized nature of its public support can lead to regional disparities in funding access and support quality [7]. SE in less economically developed or less proactive regions may face greater difficulties in securing financial resources and non-financial assistance, creating an uneven playing field.
- Across all countries, there appears to be a general scarcity of patient capital and long-term financing instruments specifically tailored for SE; they often have longer payback periods and blended return expectations (social and financial), which traditional financial markets are not always equipped to accommodate. This gap forces social enterprises to seek less suitable funding or constrains their ability to undertake long-term impact projects.
- While some countries (Slovenia, Italy) show good integration, there is often an overall gap in comprehensively combining financial support with essential non-financial capacity building, mentorship, and technical assistance. SEs, particularly early-stage ones, require more than just capital; they need support in business development, governance, impact measurement, and market access to effectively utilize funding and achieve their social missions.

E. Specifics of SE in Romania. Arguments for SE education need

SE in Romania has evolved significantly since the fall of communism in 1989. The social economy sector in Romania has experienced steady growth over the past few years. According to [14], the sector encompasses various organizational forms including associations and foundations with economic activities, cooperatives, credit unions, and certified social enterprises. Furthermore, comprehensive review of SE entrepreneurship in Romania, emphasizing the need for education, is being delivered to the user in the conversation [14]. Additionally, Romania has recognized three professional occupations in the field of social economy: Social Economy Entrepreneur (code 112032), Social Enterprise Manager (code 112036); Social Economy Specialist (code 341206).

The main challenge facing SE in Romania is related to institutional and structural. Several aspects can be considered [10,14]:

1. Despite legislative advances, social entrepreneurs still face bureaucratic hurdles and regulatory uncertainty;
2. Lack of coordination between different policy domains affecting social enterprises (limited policy coherence);
3. Challenges in establishing appropriate governance models that balance social mission with business operations;
4. Jurisdictional confusion between different levels of government and agencies.

An overview of SE education in Romania [14,21,22] showed that there is a critical need for different programs, flexible formulas, such as online or distance learning. The literature consistently identifies significant educational gaps as a fundamental barrier to the development of SE in Romania. These gaps manifest in several critical areas as follows [14,21, 22]:

- Formal education deficiencies because SE remains marginalized in mainstream educational curricula at all levels;
- Skills mismatch since traditional education fails to develop the hybrid skill set required for SE, which bridges business acumen with social impact understanding;
- Mindset limitations because educational approaches often fail to nurture the SE mindset needed for social innovation;
- Limited academic research on SE in the Romanian context;
- Knowledge transfer barriers because of the insufficient mechanisms for sharing best practices and lessons learned.

Considering the above-mentioned arguments and challenges, it has been considered that higher education institutions (HEIs) should play a pivotal role (because of their “third mission”) in addressing the challenges facing SE for several key reasons (supported by [14, 21-24]):

1. They can develop hybrid competencies including business and financial management skills, social impact assessment capabilities, stakeholder engagement approaches, ethical leadership practices, systems thinking and complexity management. SE requires a unique combination of skills that traditional educational pathways rarely provide;
2. HEIs can foster the SE mindset is fundamental to social innovation that is not innate, and it must be cultivated. This mindset includes opportunity recognition in social challenges, creative problem-solving orientation, comfort with ambiguity and risk, resilience and adaptability; ethical decision-making frameworks;
3. HEIs should provide their existing knowledge base (as an open resource) on entrepreneurship and social innovation because SE suffers from limited research and documented best practices. HEIs play a crucial role in conducting rigorous research on SE; documenting and disseminating case studies, evaluating impact

measurement approaches, analysing policy effectiveness, contributing to international knowledge exchange;

4. HEIs can create supportive ecosystems of SE (via local, national, international projects and networking). Education extends beyond formal classroom settings to ecosystem development. Modern and flexible educational initiatives can connect aspiring SE with mentors and role models, facilitate networking and collaboration opportunities, provide incubation and acceleration support; link theoretical knowledge with practical application, and create communities of practice for ongoing learning.
5. HEIs must address the unique contextual challenges of SE in different regions of Romania, as follows: post-communist legacy and its impact on entrepreneurial culture; EU integration opportunities and requirement; rural-urban divides into entrepreneurial capacity; specific regulatory and policy environment; local social needs and priorities.

Based on the above-mentioned analysis of the SE in Romania, the following conclusions have been elaborated. SE has shown promising development but faces significant challenges that limit its potential for addressing pressing social issues. Among these challenges, the need for comprehensive education in SE stands out as particularly critical. By developing appropriate educational pathways that combine business acumen with social impact understanding, Romania can nurture a new generation of social entrepreneurs equipped to tackle complex societal challenges. The development of robust SE education requires a multi-stakeholder approach involving HEIs and other educational institutions, policymakers, civil society organizations, and social entrepreneurs themselves. By investing in education that fosters both the mindset and skills necessary for SE, Romania can accelerate the growth of this sector and its contribution to sustainable social and economic development.

Having in mind the results of the comprehensive comparison study of SE in Romania, Slovenia, Germany, and Italy, analysing their legal frameworks and financial support systems, the findings and arguments presented below, in the following will be presented a framework for SE self-skills development that could be considered an example of successful solution implementation with the support of three HEIs from Romania, Slovenia, Italy and a non-governmental association from Germany.

III. The framework for social entrepreneurship self-skills development

A. Background

The framework has been developed in the context of the DigiFunCollab Erasmus+ project implementation (<https://digifuncollab.eu/>), from September 1, 2023, till

August 31, 2025. The methodological approach is a collaborative one, and was supported by four teams of trainers, researchers and practitioners in the field of SE from University Telematica Pegaso (Italy), Politehnica University of Timisoara (Romania), International School for Social and Business Studies Celje (Slovenia) and a non-governmental organization Verein für Sozialwissenschaftliche Beratung und Forschung e.V. (Germany). Thus, the developed framework considers the specifics of SE in four countries and aligns with the EU strategic framework in this field.

B. The framework for SE self-skills development

The DigiFunCollab project has successfully delivered several key outputs aligned with its objectives and that are considered methodological steps for the framework development (Fig 1):

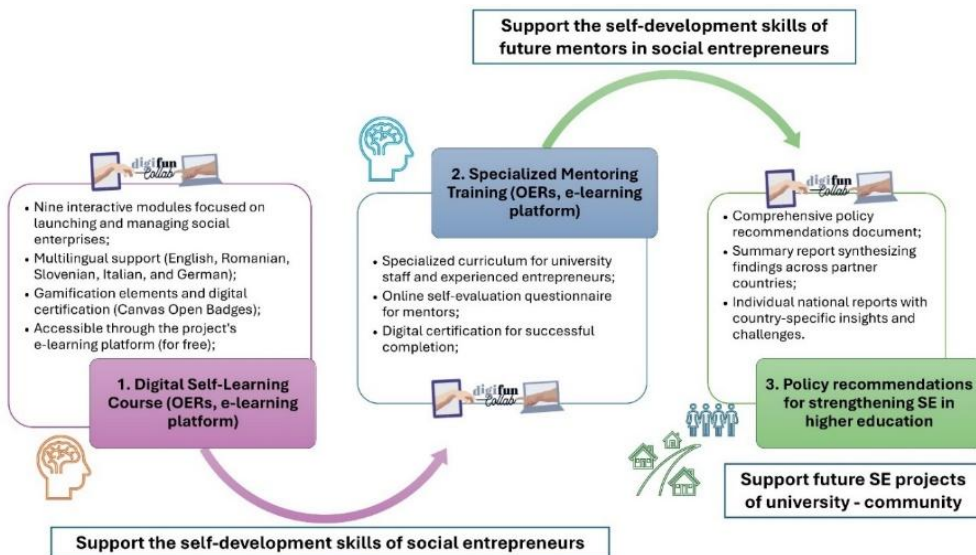


Fig. 1. DigiFunCollab framework based on the project's collaborative activities implementation within the international consortium (authors own development)

1. Digital Self-Learning course in SE - A comprehensive digital learning platform featuring (available at: <https://elearningproject.eu/courses/social-entrepreneurship-in-university/>):

- Nine interactive modules focused on launching and managing social enterprises;
- Multilingual support (English, Romanian, Slovenian, Italian, and German);
- Gamification elements and digital certification (Canvas Open Badges);
- Accessible through the project's e-learning platform (for free);

2. Specialized mentoring training module (available at: <https://elearningproject.eu/courses/teaching-social-entrepreneurship-and-mentoring-studentprojects/>) - A dedicated training module for mentors supporting SE projects;
3. A set of policy recommendations - Research-based guidance for strengthening social entrepreneurship in higher education (available at: <https://digifuncollab.eu/results/#Result4>).

The DigiFunCollab framework has been tested and validated (the digital self-learning course in SE and the mentoring training module) via project development and international competition (evaluation, comparison analysis). Students from partner institutions have developed social enterprise initiatives based on the created DigiFunCollab knowledge pool, the available framework for project development, with the support of an online mentorship schema. Further, a national project selection has been made, and 3 to 5 projects were considered for the international competition. The videos of winning projects are available at: <https://digifuncollab.eu/results/#Result3>.

C. DigiFunCollab project impact

The DigiFunCollab project has achieved significant results across multiple dimensions. In the following, the main impact indicators, facts and figures will be summarised that will demonstrate the usefulness of the designed framework (Fig. 1) and the education and certification program that has been designed and implemented.

1. Participation and engagement - The international students and HEIs teaching staff created a vibrant learning community, similar with the overall course participation are (on 30 of June 2025): 228 total participants engaged across all learning modules; 182 learners successfully completed the SE training modules; 35 mentors completed the specialized mentoring module (some of them having a certificate and online badge as recognition for their competence).

The geographical distribution of the target group demonstrates the strong need for SE education in Romania, and the quick spread and adoption of the DigiFunCollab framework in different local communities of social entrepreneurs. The number of participants registered in the e-learning platform and who have access to the training materials (Open Education Resources) is as follows: 115 participants from Romania (area of Timisoara), 74 participants from Slovenia (area of Celje), 31 participants from Italy (Napoli area) and 8 participants from Germany (Regensburg are).

2. Mentoring implementation program has been supported during several activities including a short learning activity of partners' participants with 25 mentors; 30 mentors were trained through the dedicated online module; 18 mentors earned certificates of completion. Thus, the developed mentoring open education resources

and the evaluation tools (a quiz and a gaming exercise) have been highly useful for mentors' self-training.

3. In the SE project development 111 students collaborated in 46 project groups across partner countries, from which: 72 participants developed 17 project groups from Slovenia; 26 participants have contributed to the development of 20 project groups/individual projects in Romania; 6 Italian participants have been developed 3 project groups/individual projects; 7 German participants developed 3 project groups/individual projects.

4. Award-winning social enterprise projects in the international competition (<https://digifuncollab.eu/results/#Result3>): First price, "SOW and SAVOR – Cook with care, eat with purpose", developed by a student of UPT (Romania); second price: "Roots of Legality – Social and Inclusive Garden" by students from UniPegaso, Italy; third price: "From Idea to Impact (Accessible Physical Activity)" developed by a group of students from ISSBS, Slovenia and the project entitled "Decentralized AI for Social Good: Private, Inclusive and Low-Cost AI for All Communities", developed by a group of students from Germany.

IV. Conclusions

The comparative study presented here explores the diverse legal frameworks and financial support systems for social entrepreneurship in Romania, Slovenia, Germany, and Italy. While all four countries are members of the European Union and thus benefit from overarching EU policies and funding mechanisms, their national approaches to fostering SE exhibit significant variations, shaped by historical context, policy priorities, and the maturity of their social economy sectors.

Furthermore, the study underlined the diverse national approaches to SE. The legal and financial frameworks for social entrepreneurship (SE) vary significantly across Romania, Slovenia, Germany, and Italy. Italy has the most mature and integrated system, while Germany lacks a national legal framework and relies on regional strategies.

In the presented study, the critical role that HEIs play in nurturing the SE locally and regionally has been discussed. HEIs are essential in developing digital self-learning frameworks for SE. Their "third mission" enables them to foster hybrid competencies, cultivate the SE mindset, and support community-based innovation.

In addition, there is a pressing need for harmonized legal recognition of SE across EU member states to facilitate cross-border collaboration and reduce administrative burdens. Comprehensive support ecosystems that combine financial aid with mentorship, training, and technical assistance are crucial for sustainable SE development.

Romania faces significant challenges in accessing funding, often relying on self-financing. Italy shows strong innovation in funding mechanisms, while Germany's decentralized approach leads to regional disparities.

The most important message of this study is that digital learning should be seen as a catalyst for SE skills development and should be supported by the capacity and potential of the HEIS. The DigiFunCollab Erasmus+ project demonstrated the effectiveness of digital self-learning platforms in SE education, with multilingual modules, gamification, and certification tools. The project and the presented framework (Fig. 1) successfully engaged over 230 participants, trained mentors, and supported the development of 46 SE projects across four countries, showcasing the potential of collaborative international education initiatives.

V. Recommendations. Future research

To further strengthen the SE entrepreneurship ecosystem in the countries involved in this study and across the EU, the following recommendations are put forth:

1. Harmonize and standardize legal recognition - The EU should continue to encourage and facilitate the development of more harmonized guidelines for social enterprise recognition across member states. This would reduce complexity for cross-border operations and foster a more integrated European social economy market. Countries like Germany could benefit significantly from adopting a national legal framework or a status-based recognition system like Slovenia's.

2. Enhance access to diverse funding - Policymakers in all countries, particularly Romania, should focus on improving the accessibility of funding for social enterprises. This includes simplifying application processes, increasing awareness of available funds, and developing more tailored financial instruments, such as patient capital and social impact bonds that align with the unique needs and long-term impact goals of social enterprises.

3. Integrate financial and non-financial support - There is a critical need to better integrate financial support with non-financial services like mentorship, capacity building, and technical assistance. Comprehensive support ecosystems ensure that social enterprises not only receive capital but also possess the necessary skills and knowledge to achieve sustainable growth and maximize their social impact.

4. Promote impact measurement and reporting - Implementing standardized requirements for impact measurement and reporting within legal frameworks would enhance accountability, attract more impact investors, and provide valuable data for evidence-based policymaking. This would allow for a clearer demonstration of the social and economic value generated by social enterprises.

5. Foster cross-country learning and collaboration (generalize successful programs at the national level): Facilitating structured knowledge exchange and collaborative initiatives between member states can accelerate the development of

best practices. Countries with less mature ecosystems can learn from the experiences of those with more established frameworks and funding mechanisms, while more developed nations can gain insights into innovative approaches from emerging contexts.

By addressing these areas, Romania, Slovenia, Germany, and Italy, along with the broader EU, can cultivate an even more vibrant and effective SE sector, capable of driving significant positive change and contributing to a more inclusive and sustainable future.

Potential future research directions will include the investigation of the long-term impact of digital self-learning platforms on the success and sustainability of social enterprises initiated by students and community members. This will create the basis for analysing different models of university-community collaboration to identify best practices for co-creating social innovation projects. In addition, future research will be conducted to enhance entrepreneurial activities at the HEI community level, as well as to support their sustainable and smart development [24-27]. New digital technologies must play a decisive role in supporting SE activities, through an excellent relationship between HEIs and communities.

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ACCESSIBLE E-VOTING AS A PILLAR OF SUSTAINABLE DIGITAL GOVERNANCE

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Abstract

With the expansion of digital governance, ensuring that every citizen has an equal chance to access electoral processes is rapidly becoming a key measure of democratic sustainability. In this paper, the importance of e-voting as a foundation for inclusive and sustainable digital governance is discussed. Drawing from global case studies, it examines challenges faced by persons with disabilities and digitally excluded groups in accessing e-voting facilities. It identifies key barriers such as hardware and software limitations, low digital literacy, and infrastructural inequalities. The contribution of the research comes from visionary strategic policy recommendations for improved inclusiveness and trust in e-voting technology.

Keywords

E-voting; Accessibility; Digital inclusion; Disabilities; Democracy; Sustainable digital governance; Universal design;

I. Introduction

In the digital revolution, electronic voting (e-voting) represents one of the most significant changes. In addition to making elections faster, more accessible, and easier to use, e-voting should be accessible to all citizens, including those in remote areas, those with developmental disabilities, and those with disabilities. Accessible e-voting is vital for sustainable digital governance, ensuring that democratic participation is genuine and reflects the decisions of the entire population.

The three most important elements of digital systems - long-term sustainability, inclusiveness, and trustworthiness - are supported through sustainable digital

governance. Governments should include accessibility features in e-voting platforms from the outset to address the challenge of electoral integrity and encourage voting among marginalized groups whose voting rights have historically been limited due to physical, sensory, or cognitive disabilities. In this way, the government could promise e-voting without compromising democratic standards. Accessibility is a fundamental condition for the implementation of fully democratic voting. The development of such a system faces a number of challenges, including technological, legal, social, and infrastructural. In this regard, it is necessary to implement a system that builds public trust and fosters digital literacy, including hardware and software that meet diverse accessibility needs, while preserving data privacy and security [1].

This research addresses the intersection of e-voting accessibility and sustainability. The research relies on the analysis of case studies from different countries selected according to the criteria described in the methodology section. It highlights how the design and implementation of inclusive practices in the development of voting systems across countries contribute to democratic digital governance ecosystems. It highlights best practices, challenges, and strategic recommendations aimed at a single goal: making e-voting a truly accessible tool for all citizens and strengthening democratic legitimacy.

The continuation of the work is organized as follows: Chapter 2 combines the theoretical background and literature review of accessible e-voting systems, Chapter 3 presents the methodology, Chapter 4 analyzes challenges to accessibility, Chapter 5 provides accessibility recommendations, and Chapter 6 concludes the paper.

II. Theoretical Background: Accessibility and Design Challenges in E-Voting

E-voting is a modern approach to voting. It greatly streamlines casting votes through electronic means such as e-voting machines (EVM), web-based voting systems (i-voting), and other electronic interfaces to devise the most effective way to conduct this essential process. Such a solution has to maximize the effectiveness of polls so as to enhance the voter turnout and maintain improved privacy and transparency. But now there is no single solution that will appeal to everyone. For this reason, many countries have not yet managed to implement it [2].

Accessibility of e-voting refers to the ability of all citizens to vote regardless of any type of disability. Whether they are related to the location of the voter, the level of information literacy that the voter has, or any type of disability, voters must participate in elections on an equal basis. According to Article 29 of the United Nations Convention on the Rights of Persons with Disabilities (CRPD), states must guarantee political rights, including accessible procedures and voting machines. Across Europe, few laws require accessible e-voting. Some of them only touch on the topic superficially (e.g. PSOE, VVD) [3]. In Nigeria, despite the enactment of the

Disability Discrimination (Prohibition) Act, political participation remains limited due to the absence of persons with disabilities in legislative bodies. The solution proposed by Shuaibu highlights that system reliability, inclusiveness and user-friendly interfaces must be a priority in low-resource environments [4], [2]. Accessibility of e-voting can be viewed from different perspectives:

- Physical access: How simple it is for voters to physically operate voting apparatus;
- Technical access: Support for assistant technologies including voice recognition utilities, touch and swipe devices, screen readers and magnifiers;
- Cognitive access: How easy and sensible the user interface is to help people with poor digital literacy or voters with disabilities;
- Cultural and linguistic access: Information available in more than one language and format can be understood by different populations.

From a moral perspective, given the fundamental democratic principle of equality, accessibility is essential for social stability, as it could lead to a decline in public trust and decreased political engagement. Failures during the 2000 US presidential election or the 2008 Finnish local elections are evidence of how poor design can lead to invalid votes and loss of trust [5]. Accessible e-voting systems must overcome a wide range of technical and design barriers that impact usability for people with different types of disabilities. These challenges can be of various types. From the physical layout of the device to the system's logic, and the clarity and intuitiveness of the interface. Lack of attention to these aspects of the system when creating it can significantly affect the results of the electoral process, but also violate a fundamental democratic right [6]. Some of the most important challenges are presented below.

A. Hardware Interface Limitations

Many e-voting systems use touchscreens, as do almost all devices today. However, they are not the ideal solution for people with visual impairments or those who rely on physical aids for navigation. Blind or visually impaired people will be denied the opportunity to vote if the machines lack a Braille keyboard, audio output, or tactile indicators [7].

B. Software Barriers and Compatibility

By contrast, software generates different kinds of problems. Without rigorous adherence to accessibility suggestions like WCAG (Web Content Accessibility Guidelines), their consumer interfaces are often too complicated, cluttered, hard to use, or devoid of screen reader functionality. Voting options can be difficult for users who depend on assistive software programs like JAWS or NVDA to understand.

C. Lack of real-time support and flexibility

Most e-voting systems lack adaptive features, which allow some basic adjustments, such as changing font shapes for blind persons, real-time translations for speakers who do not understand the prevailing language of the software, or text-to-speech. These inadequacies can affect all classes of individuals, but mainly affect old citizens and people who experience cognitive or language processing disorders, which in these groups results in a low percentage of individuals. In addition, the systems that do not allow voters to navigate backwards or repeat the instructions further complicate the experience for these users.

D. Accessibility and security trade-offs

Maintaining a high degree of safety while ensuring accessibility is another challenge. It remains very tough to find a balance between the two without compromising either. For example, customers with disabilities may additionally experience disruptions due to multi-element authentication or CAPTCHA verification [5].

E. Infrastructure and Maintenance Disadvantages

Even if a system is designed with solutions to all the aforementioned problems in mind, it is impossible to achieve good results if polling stations lack the necessary hardware or trained personnel. Poor internet connectivity, outdated firmware, and lack of device calibration will significantly hinder the use of the system, and in the worst case, lead to system failure, especially in rural or underdeveloped areas.

III. Methodology

The paper is based on case study analyses conducted across different countries. The research materials were selected in a way to include the diversity of geographical, technological, and political approaches to e-voting. Publicly available study databases, including IEEE Xplore, Scopus, ScienceDirect, and Google Scholar, were searched. The queries used were “accessible e-voting”, “e-voting and people with disabilities”, and “e-voting and digital government”. The focus was on studies published after 2010 in English. Criteria that further narrowed the selection:

- geographical diversity,
- inclusiveness of access characteristics,
- inclusiveness of marginalized user groups,
- integration with national or regional digital governance strategies,

- documented results, assessments, or challenges, which allow the assessment of success or failure factors.

Estonia, Indonesia, Bangladesh, and other international locations were specifically selected for meeting these requirements. The available documented information allows for a comparative analysis of the situation in different countries. The variables relevant to the topic of accessible and secure e-voting systems were selected:

- Type of accessibility features provided;
- Technological infrastructure and devices used;
- Legal or institutional frameworks for support;
- Reported technical or societal challenges;
- Trade-offs between security and usability.

The results of the analysis provide an overview of how different systems work in terms of accessibility and inclusion. The analysis is not intended to strictly compare systems, but to identify key defaults, challenges, and strategies that can help future implementations increase inclusion in e-voting.

IV. Strategic and Global Perspectives

If the goal is a fully integrated system, accessibility cannot be viewed in isolation. It requires multi-stakeholder collaboration, legal harmonisation, and coordinated policy implementation. Yuliani proposes the Fuzzy Analytic Hierarchy Process (AHP) Phase in system evaluation to rank the criteria listed above and select a technology based on an informed decision [8]. A sustainable accessibility strategy must include:

- Early accessibility testing;
- Mechanisms for regular feedback gathering from people with disabilities;
- Investment in research and development of inclusive technologies.

In addition to consistency, such a framework also ensures social legitimacy and greater public trust in digital systems and their digital governance. By exploring the current state of the art in this area and examining international case studies - both successes and failures - we can better understand whether and how accessibility is currently integrated into digital governance systems around the world (Table 1).

Table 1. An Overview of Global E-Voting Systems' Accessibility

Country / System	Key Features	Accessibility Challenges	Reference
Estonia	- Digital ID card system - X-Road data exchange platform	- Not all citizens are advantaged equally	[9]

	- Screen reader compatibility - Strong encryption	- Issues with the elderly, rural populace, and those with disabilities	
Indonesia	- Efficiency and transparency in e-voting - Ongoing exploration of digital democracy	- Constant digital divide - Limited access for remote populations and voters with disabilities	[10], [11]
Voatz & Luxoft	- Biometric authentication for secure voting	- Lack of universal design - Limited clear accessibility features	[12]
POLYAS & Polys	- Focus on auditability and transparency - Citizen participation emphasis	- Common absence of accessibility standards	[12]
Bangladesh	- Biometric authentication - Integration of local cultural/ethical frameworks (Islamization of Knowledge)	- Complexity in balancing technical and cultural values - Accessibility implementation is still in progress	[13]
Austria	- Developed specifically for visually impaired voters - Tactile keypad, audio guidance, and simplified navigation - Based on inclusive design principles	- Limited deployment - Training and public awareness is required to maximize the purpose	[14]
Uzbekistan	- AI features: facial recognition, NLP - Low-power infrastructure (Helium blockchain)	- Challenges of electricity and internet access in remote areas	[15]
Gesture-Enhanced	- Gesture-based interface (eyebrow/nose)	- Still in prototype phase	[16]

Intelligent Blockchain Voting System	- High recognition accuracy (>90%) - Designed for digital illiteracy		
Sri Lanka	- Multi-modal voting system for the visually impaired (Button Tactile & Touch Tactile ballots) - Universal Design & UCD principles - Audio instructions and tactile overlays	- Visual design challenges in tactile layouts - Preference and usability vary across interfaces - Still a prototype	[17]

Countries like Estonia provide examples of digital voting systems that integrate security, transparency, and accessibility. The Estonian system includes features such as screen reader compatibility and strong encryption. A national digital ID card system that provides every citizen with a secure digital identity and access to a wide range of services is a central part of this system. The X-Road platform also enables data exchange between different systems, keeping it secure and transparent. The Estonian program has issues with inclusivity despite its effectiveness and inventiveness. The authorities recognize that not everybody, in particular the elderly, the rural inhabitants, and people with disabilities, benefits equally from digital services. While this model is definitely moving towards improvement, users with physical or mental impairments or lower digital literacy are still not adequately served. Simple interfaces, multilingual support, user training programs, and compatibility with a wider range of assistive technologies could alleviate these issues [9].

Another country that shows how much e-voting improves efficiency and transparency is Indonesia. Nevertheless, the digital divide continues in spite of laws (Law No. 8/2016) created especially for individuals with disabilities. Pilot tests have also been conducted. They confirmed allegations of exclusion of blind/deaf voters, as well as the very low level of digital literacy that is still not being addressed. Ways to ensure equal access and foster digital literacy, especially among groups with disabilities and those in remote locations, are still being sought [10], [11]. However, the local elections in Sleman Regency, Indonesia, serve as a real-world example of how technical support can help older voters lacking sufficient digital literacy successfully participate in the election. Despite minor technical issues, key accessibility indicators were adequately met [18].

Systems like Voatz and Luxoft use biometric authentication, enabling voters to participate securely in elections. Additionally, platforms like POLYAS and Polys focus on auditability and transparency, giving citizens a voice. However, despite

these benefits, a common limitation across most systems is the absence of clear accessibility features or universal design standards [12].

The implementation of digital voting technologies in Bangladesh demonstrates the complexity of accessible e-voting as a pillar of sustainable digital governance. Ensuring accessibility for all citizens requires not only technological solutions such as biometric authentication and voter information systems, but also the integration of democratic principles with local cultural and ethical values, as exemplified in the Bangladesh Islamization of Knowledge (IOK) framework [13].

The EVITA version (Austria) is a sophisticated European system that uses identity domain separation and hardware safety modules (HSMs) to ensure anonymity and verifiability without sacrificing accessibility. The version also includes a fallback option that allows voters to switch to traditional voting if the digital method fails, which is especially helpful for voters with disabilities, low digital literacy, or infrastructure issues [14].

The results of a study on citizens' perceptions of blockchain-based e-voting systems in Uzbekistan highlight the key role of accessibility and user-centred design in the successful adoption of digital voting technologies. By combining blockchain for data transparency and integrity with artificial intelligence-based features such as facial recognition and natural language processing, the system offers inclusive access to voters regardless of language, location, or socioeconomic status. Low-power infrastructure, such as the Helium blockchain, further enables access in remote locations, areas with limited access to electricity or the internet [15].

On the other side, researchers who assessed in "A Gesture-Enhanced Intelligent Blockchain Voting System" say that a gesture-based e-voting system offers significant evidence that accessibility and security are not just a pipe dream. They can exist in digital voting solutions. The Gesture-Enhanced Intelligent Blockchain Voting System is a research prototype, developed and tested in a controlled academic environment. It is not yet in real-world use, but it suggests a way to implement an accessible e-voting system. The systems are based on eyebrow and nose movements and achieve recognition accuracy of over 90%. The interface is designed to be adaptable and easy to use, allowing voting even for groups that are not digitally literate. Users from groups with disabilities rated the system as 90% satisfied. The author's commitment to exploring even more inclusive techniques, such as emotion recognition or vein patterns, shows that accessible and sustainable digital governance that puts the needs of all citizens at the centre is not unattainable [16].

A user-centric design approach is required to achieve true access in e-voting systems. A Sri Lanka study developed a multi-model e-voting prototype for voters, especially for visually impaired voters. The solution included Button Tactile (BT) and Touch Tactile (TT) ballots, both optimized for usability, privacy, and independence. The BT ballot, which included four physical buttons, was preferred

for simplicity, while the TT ballot offered slightly higher efficiency and accuracy. This research highlights that accessibility must go beyond compliance to deliver an equitable user experience [17].

While security and public trust remain fundamental challenges, the experiences of countries around the world illustrate that e-voting systems must explicitly address usability and inclusion challenges from the outset, such as providing solutions for visually impaired voters and other groups with disabilities to ensure equal participation [18].

V. Recommendations

In order to ensure e-voting systems support sustainable and inclusive digital governance, targeted strategies need to be applied that specifically address access to accessibility and security concerns. The following recommendations address the actions that will ensure equal participation of all citizens in the voting process, including persons with disabilities.

- Inclusive design of hardware and software:

System hardware elements should have built-in features that will enable improved accessibility. This includes Braille keyboards, audio output, haptic feedback, high-contrast interfaces, and alternative input methods (e.g., sip and puff devices). Software should be implemented adaptively and intuitively. Screen readers, adjustable fonts, and multilingual options should be integrated into the interface to accommodate different disabilities. One of the newest approaches for voter authentication is designed for voters with voice-based biometric systems, especially those with disabilities. By enabling safe login via voice patterns, these systems provide a touch-free, accessible solution for visually or dynamically limited voters. This law authentication improves inclusion, supporting the rights mentioned directly in the rights of the rights (UNCRC) of individuals with rights mentioned in Article 29 of the United Nations Conference, while maintaining accuracy [19].

- Adherence to international accessibility standards:

Systems should be aligned with standards such as the Web Content Accessibility Guidelines (WCAG). Country-specific legal requirements should also be met.

- Implementation of security and privacy protocols:

Sensitive voter data must be protected through end-to-end encryption. Data leaks must not occur. Secure biometric authentication and transparent audit trails for voters who cannot use standard methods will address concerns about accessibility features.

- Improving voter education and digital literacy:

Creating targeted campaigns to raise awareness of the importance of this way of voting. Explaining in detail how to use it through various communication channels to familiarize all voters with the e-voting processes and accessible tools. On the

other hand, launching a training program to educate officials so that they can effectively assist voters who need assistance [2].

- Involving stakeholders in co-design:

Whether a solution is of the highest quality will be known if tested by the people for whom it was designed. Therefore, involving people with disabilities in the design and testing phases will ensure that solutions meet the needs of real users. Much research has shown that this approach reveals barriers as standard-based testing misses. Tools such as the System Usability Scale (SUS) or the Software Usability Measurement Inventory (SUMI) are recommended [20], [4], [21].

- Providing infrastructure and technical support:

To ensure hardware and software are fully operational and available, without unwanted interruptions or crashes during the election, especially in remote and rural areas, it is necessary to provide sufficient technical support and maintenance.

- Monitoring, evaluation, and adaptation:

Establishing appropriate systems that will perform monitoring and continuous monitoring will ensure the timely detection of errors. The analysis and evaluation of the work will assess the effectiveness of accessibility functions and the overall user experience. With the help of the results of these processes, or their feedback, iterative improvements to the system can be made, which will ultimately lead to a system that meets everyone's needs and meets all the conditions that such a system should meet.

VI. Conclusion

Accessible e-voting really represents the first step required in achieving inclusive, equitable and sustainable digital governance. Introduction of systems that facilitate access to other areas, such as electoral safety and transparency, will increase equality for all. We all need to work together to break the obstacles in access. The governments ensure democratic values, empowering all voters to reach the electoral process independently and in security, regardless of physical, sensory, or intellectual ability and encourage citizenship to participate in the process. This increases the validity of elections.

Finally, e-elections that are accessible are more important than a technical fixation. It is one of the key guarantees of the Democratic system of flexibility and inclusion. Exhibitions should continue the stage of the center despite the rapid rhythm of digital technological progress to ensure that any citizen does not follow the values of equality, participation and confidence inherent in a durable democratic society.

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CONTRIBUTIONS AND DEVELOPMENT REGARDING SIX SIGMA MANAGEMENT SYSTEM IMPLEMENTATIONS IN A WIRE DRAWING COMPANY

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Abstract

Wire drawing is a process of cold plastic deformation of metals and alloys to obtain wires by forcing the metallic material through a calibrated hole whose cross-section is smaller than the cross-section of the initial material. Based on this, the article presents the implementation of this concept in the wire drawing section of a factory in the field. It thus presents the Lean profile in the wire drawing section over a certain period, the implemented Six Sigma in the energy-metallurgy section and comparative aspects regarding the application of Six Sigma in the "Metallurgical" area, the Six Sigma audit results, autogenerated actions in PS planner, close action percentage per Six Sigma and sigma flow.

Keywords

wire; drawing; Six; Sigma; audits; quality

I. Introduction

Drawing is a process of cold plastic deformation of metals and alloys to obtain wires, by forcing the metallic material through a calibrated hole whose cross-section is smaller than the cross-section of the initial material. Following the application of the drawing process, the surface of aluminium and copper wires must be smooth, without oxidation spots, grooves, scratches, cracks, chips, scales, bulges, twists, and excess drawing oil.

In a factory that produces wires by drawing, drawing is divided into two important categories, depending on the wire diameters produced. Heavy drawing is defined as follows, which is obtained by:

- round aluminium wire with diameters 9, 12, 15, 20, 25 mm (heavy aluminium drawing)
- round copper wire with a diameter of 8.0 mm (heavy copper drawing)

For this category of drawing, the raw material is brought from the raw material warehouse, located in the immediate vicinity of the drawing area, using the overhead crane. The wire is placed on the unwinder of each die. From the unwinder, the wire is passed through the range of dies, depending on the desired final diameter. After this operation, the dies are mounted in the die holder. From the final die, the wire is passed to the wire accumulator and then to the double winder. The aluminum wire is drawn starting from the diameters indicated above. The wires obtained from the heavy drawing process constitute a finished product for electrotechnical purposes or by-products used in the construction of other types of insulated or non-insulated electrical conductors. Light drawing is the second category of drawing through which the following is obtained:

- aluminum wire obtained from the heavy drawing process with a maximum diameter of 4.5 mm for T5 (light aluminum drawing);
- copper wire with a diameter of 2.5 mm (light copper drawing);

The raw material is brought from the staging area, after the heavy drawing operation or annealing heat treatment. Six Sigma represents a method of organizing and managing a workspace or workflow and aims to improve efficiency and quality by eliminating waste, improving workflow and eliminating useless processes/activities. Within the wire drawing section, we have thought, realized and implemented elements of Six Sigma as presented below to ensure a predictable, organized and safe workplace. The method is based on the Five Sigma methodology and was empowered by including "safety" as one of the pillars. The Five Sigma process is a structured program to systematically achieve: organization, cleanliness and standardization in the workplace. The content of the Five Sigma is as follows: - seiri (Sorting); - seiton (Stabilizing order); - seiso (Shining); - seiketsu (Standardizing); - shitsuke (Supporting change). To the five pillars, a sixth one was added, which refers to occupational safety. Using the 5 Sigma presented above ensures a safe, clean and profitable workplace. Lean Manufacturing – schematically presents the concept. Lean manufacturing based on Six principles is defined as: 1. Sorting – Organizing; 2. Establishing Arrangement – Order; 3. Shine – Clean; 4. Standardization - Standardized Cleaning; 5. Support – Discipline; Six. Safety - The Only Way to Advance [1-3].

II. Comparative aspects of the application of Six Sigma in the “Metalurgical shop”

The introduction and application of the Six Sigma system is a complex activity, of which several elements will be presented below. Figure 1 presents the application of the SixS method in the metallurgy-heavy wire drawing section.



Fig. 1. Applying Six Sigma in the metallurgy department – cleaning the workplace

Figure 2 presents the application of Six Sigma in the heavy wire drawing section. Figure 2a presents the cleaning and painting of the workplace. Figure 2b presents the establishment of the arrangement of the wire coils and figure 2c presents the standardization. Figure 2d shows workplace cleaning.

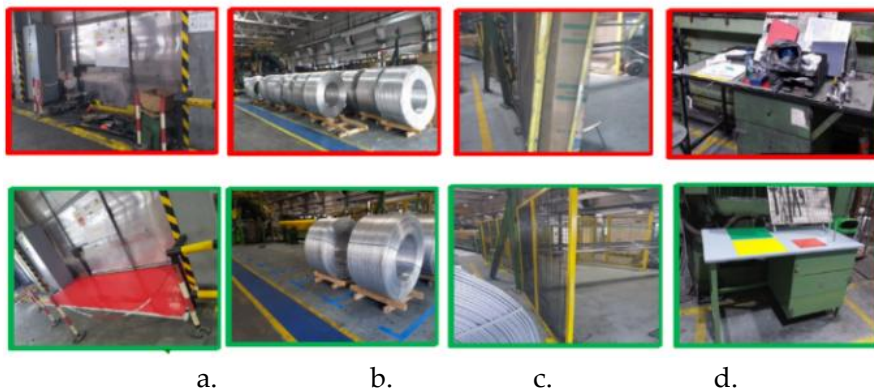


Fig. 2. Applying Six Sigma in the heavy wire drawing shop

Within the light wire drawing section, figure 3 presents the cleaning of machines and auxiliary installations as well as their painting.



Fig. 3. Six Sigma - cleaning and painting in workplaces at the light wire drawing shop

Figure 4 also presents the cleaning and painting of the coil supports, the command-and-control cabinets and the auxiliary equipment.



Fig. 4. Six Sigma Application in light wire drawing shop

A. Six Sigma audits

To comply with Six Sigma requirements, periodic audits will be conducted [4,5]. The audit is planned by the area manager, inviting the auditor assigned to the area in charge and support from the continuous improvement department. An action plan for the wire drawing section is presented in figure 5.

GMR Logo: 0 "Activity complete on on target", 1 "Activity incomplete - ongoing", 2 "Activity not started yet"									
Item No.	Actions				Recommendation/Corrective action	Responsible for implementation	Status	GMR Status	GMR
	Date	Location	Description	Photos Before					
1	6-Jan-22	Treflarea	Training operation Treflarea - Sorting activity (Train the operators in Red Drawing Area)		Need to cover all the shifts	Tedor / Maria G.	26-Jan-22	1	The training for 2 shifts was done during the Feb off event, needed for other 3 shifts.
2	6-Jan-22	Treflarea	Organizare zona vichetie rosii + Completare Tablei de de Organizare (Organize the red tagg Area + completed the OS Area)		To be painted in red the area + update the OS board	Tedor G.	26-Jan-22	1	Done
3	6-Jan-22	Treflarea	Sortarea zilnica la masini (Daily sorting and cleaning activity at the machines)		Sortarea zilnica si curatenia de la masini la sortarea zilnica (Daily activity responsible)	Dorota M./Team operators	30-Jan-22	1	Activity is done continuously every day.
6	6-Jan-22	L1/L3	Curatenia zonei Treflarea L1/L3 (Cleaning oil at L1/Wire drawing)		Clean and eliminate the cause	Dorota M.	16-Jan-22	1	The Red drawing around L3 was cleaned of oil
7	7-Jan-22	T1	Reparare T1 legat cu sursele electrice (Repair T1 with electrical sources)		Find other solution	Chelaru M.	26-Jan-22	1	Done - need to be painted
8	7-Jan-22	L1	Capacitatea de curatenie a cuprului (L1) (Copper capacity cleaning)			Chelaru M.	16-Jan-22	1	The machine was cleaned and covers removed
11	14-Jan-18	T1	Amplasarea zonei materialelor (Change the area of aluminum coils)		Area to be defined: See if it is possible to put a profile row	Dorota M.	30-Jan-22	1	was done
12	6-Jan-22	T1	Parcarea de comandă deteriorată (Control panel damaged)		Repair or change the panel	Chelaru M.	30-Jan-22	1	Done
13	7-Jan-22	T2	Motor de antrenare îngrat în gâtul legat cu sursele electrice (Motor drive gear in the neck of the gear with electrical sources)			Sanda Viorica	9-Feb-22	1	Done
14	6-Jan-22	T1	Supportul de antrenare T1 (Supports take up round supports)			Dorota M.	9-Feb-22	1	Done
15	6-Jan-22	Treflarea	Scindarea sârlei în caz de deteriorare (Change the belt in case of damage)		Change with new ones	Maria Cosma	9-Feb-22	1	Done
16	6-Jan-22	L1	Cardul protecție L1 deteriorat (Protection fence damaged L1)		Need to be repair	Chelaru M.	23-Jan-22	1	Done

Fig. 5. Action plan for the wire drawing shop

Non-conformities identified during the Six Sigma audit will automatically be assigned as tasks. Activities that are not completed within a reasonable time will be presented in the weekly management meetings. For the Six Sigma audits, a list of

responsible people is drawn up. In the continuation of the activities, the graphic tracking of the results from the Six Sigma audits and the closure of non-conformities will be carried out.

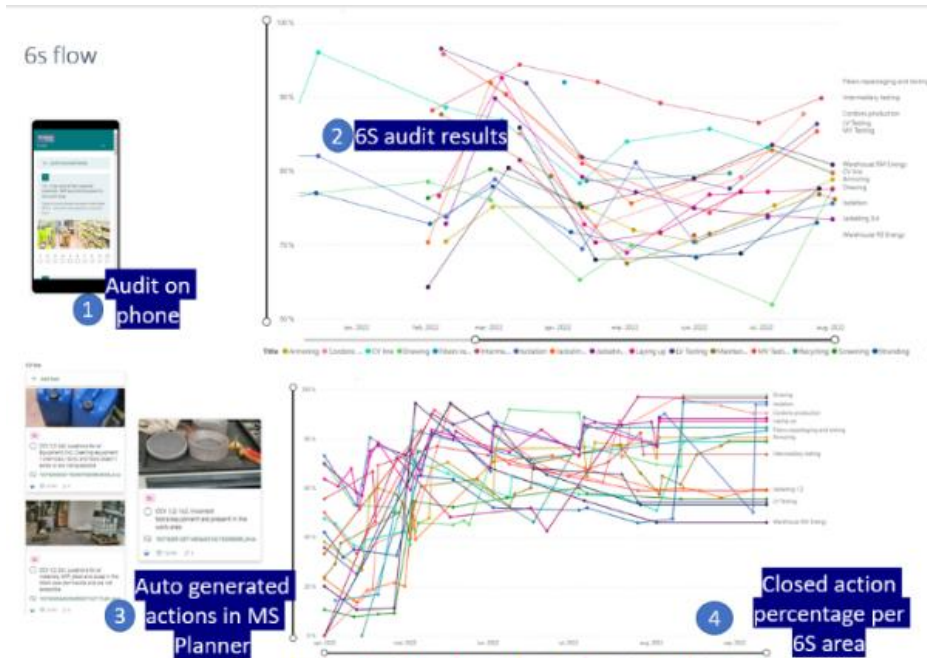


Fig. 6. Graphical tracking of results from Six Sigma audits

Fig. 7 presents the flow of actions to be done within Six Sigma activities.

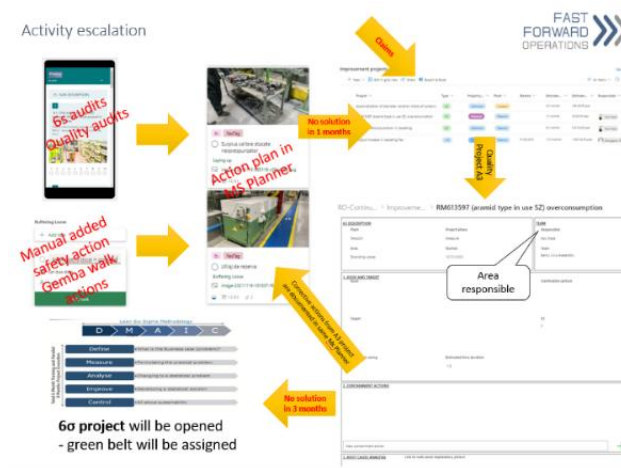


Fig. 7. Flow of actions within Six Sigma activities

As a result of the Six Sigma audit, each area manager within the company must close the non-conformities in the Planner within one month. Figure 8 presents examples of applying the 6S methodology in the Energy factory.



Fig. 8. Six Sigma improvements

Each area manager within the company must close the non-conformities in the Planner within 1 month. Figure 9 shows examples of applying the Six Sigma methodology in the wire-drawing shop as a result of the activity during Six Sigma audits.

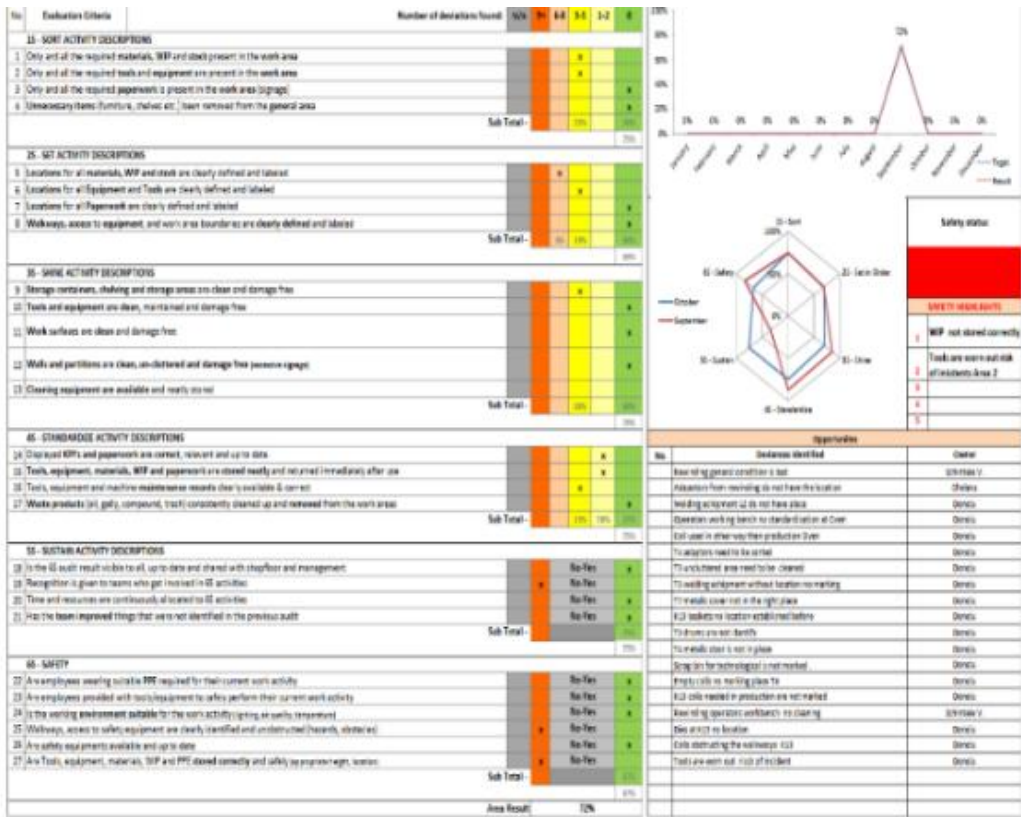


Fig. 9. Six Sigma audit presentation format

A part of the result of the Six Sigma audits in the wire drawing area is presented in figure 10.

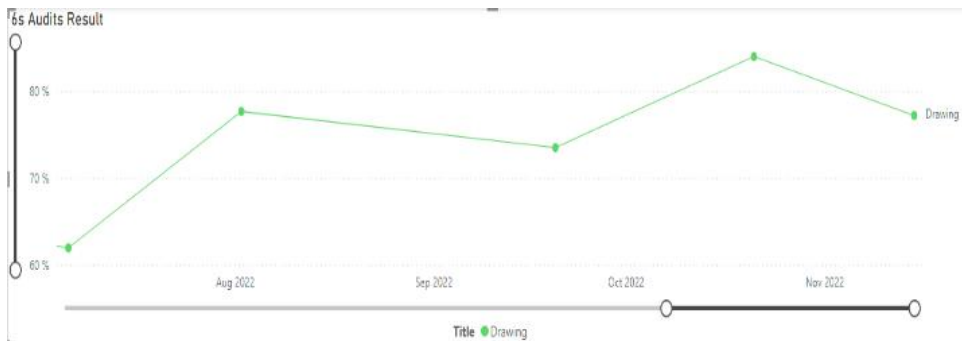


Fig. 10. Six Sigma audit result represented graphically

As can be seen from figure 27, a level of fulfilment is found as follows: July- 62%; August-77%; September-74%; October-84%; November-79%. Tips for a successful implementation of Six Sigma can be:

- establishing a calendar for support activities and respecting it;
 - communicating with employees to empower their sense of involvement and listening to what they have to say;
 - involving employees in supporting Six Sigma improvements;
 - taking advantage of the tools used daily (checklist), analyzing what the opportunities are
 - reinforcing the idea that audits are an opportunity for improvement, so as not to highlight weaknesses;
 - using the network with other facilities of the Group and HQ;
 - encouraging operators to develop daily with the support of the 6S Council;
- Communication of the results of the 6S audits is done monthly by e-mail to all company management, as can be seen in figure 11.

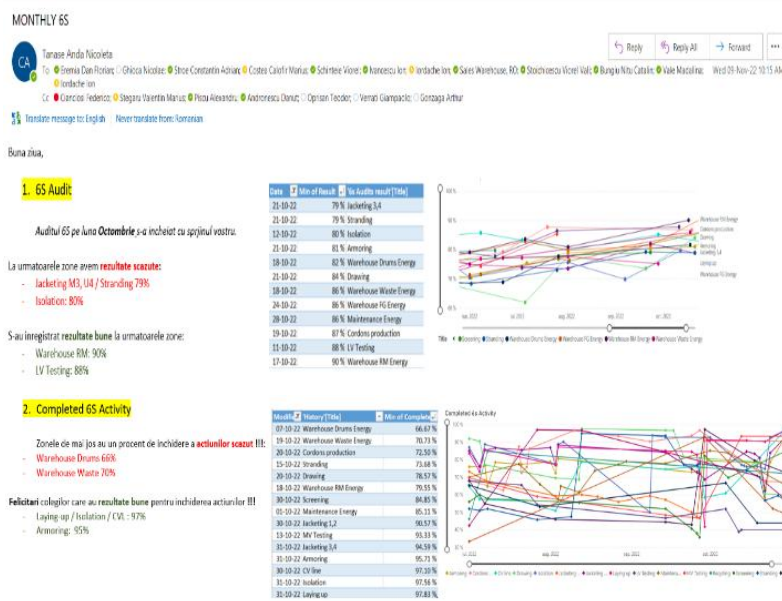


Fig. 11. Communicating Six Sigma audit results

B. Process data analysis during manufacturing

The technological process data monitored in the production of electrical cables is a function of the technological stage. For metallurgy, wire drawing and cabling processes, the most important process data are: electrical resistance, mechanical resistance, elongation and weight. Quality parameters (tensile strength and elongation) are monitored by the Quality Department. The parameters monitored by the Production Department are electrical resistance and weight, as presented in figure 12. Here are presented the data for each column:

- ID - individual numerical code for each entry;

- date when the entry was made;
- material - each product has a unique 8-digit SAP code. For example - power cables start with the number 2. Fiber optic cables start with 6;
- operation - the different manufacturing stages are recorded in SAP by numerical values. For example, 10 is Wire Drawing, 20 is Cabling, etc.
- semi-finished product - the semi-finished product at the respective operation. For example, AL 150 RMC means round multi-wire aluminium conductor with a cross section of 150 mm;
- weight: value measured with an electronic balance;
- nominal electrical resistance and measured electrical resistance;

1171	05.01.2019	20224596	0010	AL 240 SMC	634,09	125	126,31		
1172	05.01.2019	20224596	0010	AL 240 SMC		125	127,81		
1173	05.01.2019	20021135	0010	AL 70 RMC		443	446,2		
1174	05.01.2019	20224744	0010	AL 120 SMC		253	261,41		
1175	05.01.2019	20224744	0010	AL 120 SMC	307,07	253	258,55		
1178	05.01.2019	20224596	0010	AL 240 SMC		125	127,19		
1179	05.01.2019	20021135	0010	AL 70 RMC		443	446,38		
1180	05.01.2019	20021135	0010	AL 70 RMC		443	449,13		
1181	05.01.2019	20021135	0010	AL 70 RMC		443	449,13		
1182	05.01.2019	20224744	0010	AL 120 SMC		253	256,29		
1183	05.01.2019	20021135	0010	AL 70 RMC		443	446,4		
1184	06.01.2019	20224744	0010	AL 120 SMC		253	258,57		
1185	06.01.2019	20224596	0010	AL 240 SMC	613,29	125	126,72		
1186	06.01.2019	20224744	0010	AL 120 SMC		253	257,2		
1187	06.01.2019	20021135	0010	AL 70 RMC		443	446,49		
1188	06.01.2019	20236430	0010	AL 150 RMC	364,69	206	208,79		
1189	06.01.2019	20021135	0010	AL 70 RMC		443	449,43		
1190	06.01.2019	20224744	0010	AL 120 SMC		253	258		
1191	06.01.2019	20021135	0010	AL 70 RMC		443	446,43		
1192	07.01.2019	20021135	0010	AL 70 RMC	169,65	443	451,53		
1193	07.01.2019	20236430	0010	AL 150 RMC		206	209,35		
1194	07.01.2019	20236430	0010	AL 150RMC		206	209,34		

Fig. 12. Presentation of process data for the wire drawing operation

C. Overall equipment effectiveness (OEE) analysis wire drawing

Very often, in industry, bottlenecks occur that are crucial to discover. Their identification is carried out based on analyses, provided by reports, such as:

- job performance.
- operator performance.
- production cycle study.
- machine and equipment utilization.
- downtime history.

All these elements allow production managers to make optimal decisions. Overall Equipment Effectiveness (OEE) is a key performance measure used in production. OEE calculations help evaluate the efficiency of equipment or

processes. They provide information about how well a machine or production line works. OEE is calculated by measuring three crucial factors:

- Availability - represents the percentage of time that equipment is available and ready for production. It weighs downtime due to breakdowns, changes, and planned maintenance. The formula for calculating availability is:

$$\text{Availability} = \text{Actual Production Time} / \text{Potential Production Time} \times 100\%$$

- Performance - performance evaluates the speed at which the equipment is operating compared to its maximum potential speed. It takes into account factors such as machine slowdowns, idling and minor stops. The formula for calculating performance is:

$$\text{Performance} = \text{Equipment Operating Speed} / \text{Potential Operating Speed} \times 100\%$$

- Quality - Quality measures the ratio of good quality output to total output. It takes into account defects, rework and scrap. The formula for calculating quality is:

$$\text{Quality} = \text{Good quality output} / \text{Total production quality} \times 100\%$$

Once the availability, performance and quality calculations are completed, they are multiplied together to obtain the Overall Equipment Effectiveness (OEE). The OEE formula is as follows:

$$\text{OEE} = \text{availability} \times \text{performance} \times \text{quality} \times 100\%$$

Monitoring machine performance allows managers involved in production to analyze, interpret and make decisions according to the data received to maximize their efficiency. Among the indicators monitored by managers is OEE (Overall Equipment Effectiveness), along with its three components: availability, performance, and quality. Sometimes, when there are automated data acquisition processes in real time, obtaining OEE is within reach of anyone who has the right to access such data. Practically in this case, the responsibility for calculating OEE falls to the software program that acquires the data from the machine. This method is preferable because it leaves no room for negligence and interpretations regarding the collected data. The second advantage is that the same rules are applied in data collection and decisions are made under the same conditions, so that comparisons can be made regarding the evolution of the machine. In the case of manual data recording, there are situations when the data is “filtered” which leads to a lower accuracy of the information obtained. In this case, there must be a person responsible for recording the data necessary for the OEE calculation. Generally, this responsibility falls on the team leader who, at the end of the work shift, processes it and sends it to higher levels: foremen, workshop heads, and section heads. From a quality management perspective, drawing a Pareto chart is very important because it provides essential data on product quality. A Pareto chart is a way to visually classify the causes contributing to a given result. This chart is like a bar chart, in which they are arranged in descending order of magnitude. Pareto charts are used for problem analysis, process improvement, root cause analysis, and process redesign. This type of chart helps to:

- identify which causes contribute the most to the result;
- identify what is truly important versus what is not;
- prioritizing problems;
- identifying where action needs to be taken.

In quality, the Pareto chart is used to understand the causes of poor results. Thus, it can be seen quite clearly what contributed to the appearance of a problem. The following characteristics make a Pareto chart an excellent visualization tool:

- it is easy to understand and interpret – a Pareto chart is very simple to read and interpret;
- it is simple to create;
- no sophisticated software is needed to create a Pareto chart; all you need is Excel;
- it helps to separate essential but limited causes from multiple but non-essential causes.

Using the Pareto chart, the key causes that lead to most problems can be separated and thus, attention can be focused on a limited number of causes. Figure 13 presents the “Overall Equipment Effectiveness” report for one of the wire drawing machines compared to a calendar month.



Fig. 13. „Overall equipment effectiveness” report for a calendar month

II. Conclusions

The article presents the Six Sigma method of organizing and managing work activities in an electrical cable manufacturing company within the framework of improving the quality management system. It presents several work stages carried out in this context and the Six Sigma audit, which attempts to highlight the resulting advantages and benefits.

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