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TOWARDS SUSTAINABLE DIGITAL TRANSFORMATION IN INDUSTRIAL ENTERPRISES WITH A FOCUS ON THE CZECH REPUBLIC*

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Abstract. This article presents a comprehensive review of current trends, barriers, and opportunities in sustainable digital transformation within the manufacturing sector, with an emphasis on Central and Eastern Europe. Drawing on a systematic analysis of 85 peer-reviewed studies published between 2020 and 2025, the review identifies the main factors influencing the successful adoption of information systems (IS) and artificial intelligence (AI) in industrial enterprises. The results highlight that the most significant long-term performance and sustainability gains are achieved when technological innovation is combined with the development of digital skills, open organizational culture, and strategic approaches to environmental management. The review further outlines persistent barriers – including human, organizational, and technological challenges – as well as the lack of locally tailored frameworks and empirical evidence for Central and Eastern Europe. By synthesizing these findings, the article provides practical guidance and conceptual clarity for both practitioners and researchers aiming to support effective and sustainable digital transformation in manufacturing.

Keywords: digital transformation; Artificial Intelligence (AI); sustainability; information systems; manufacturing; organizational culture; Central and Eastern Europe; Czech manufacturing sector

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1. Introduction

The global manufacturing industry is experiencing a fundamental digital transformation driven by technologies associated with Industry 4.0 – such as artificial intelligence (AI), the Internet of Things (IoT), and big data analytics – which are rapidly reshaping production processes and business models (Chilunjika, 2024; Li et al., 2025). These innovations deliver higher operational efficiency, enable real-time, data-driven decision-making, and support the development of new business models oriented towards sustainable growth (Li et al., 2025).

Simultaneously, the imperative of sustainability is gaining prominence. In response to climate change and pressure to reduce emissions, enterprises are increasingly required to pursue sustainable operations alongside digital transformation (Ezzat, 2023). The World Economic Forum underscores that companies must align digital and sustainable transformation, as only their integration can ensure compatibility with low-carbon economic

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goals (Ezzat, 2023). Advanced digital technologies can significantly reduce the environmental footprint of manufacturing – through sustainable product design, circular approaches, and improved efficiency of resources – which strengthens long-term resilience and competitiveness (Ezzat, 2023).

For the Czech Republic, with its highly industrialized economy and strong integration into international value chains, these global trends are especially relevant. The manufacturing sector forms the backbone of the national economy, with the automotive industry alone accounting for roughly a quarter of total exports (Keay, 2024). However, the historical advantage of low-cost labor is now diminishing. The Czech economy faces the so-called middle-income trap, where wage and price growth outpaces productivity increases, undermining long-term competitiveness (Keay, 2024). Chronic labor shortages – particularly of skilled workers – further exacerbate these challenges, as the country's unemployment rate remains among the lowest in the EU, intensifying wage pressures and increasing unit labor costs (IMF, 2024).

Alongside these external pressures, domestic barriers persist. Excessive administrative burden and slow permitting processes hinder business development, and international organizations recommend simplifying regulation and further digitalizing public administration (IMF, 2024). Another persistent challenge is the relatively low level of digitalization among many firms, especially small and medium-sized enterprises (SMEs): only about half of Czech SMEs achieve basic digital intensity, compared to an EU average of approximately 58% (European Commission, 2024). This digital divide leads to lower productivity and innovation in lagging firms, ultimately constraining sectoral growth.

From a sustainability perspective, the Czech manufacturing sector is also characterized by high energy intensity, with much of its energy mix still reliant on fossil sources (IMF, 2024). The path to climate neutrality by 2050 – aligned with EU strategy – will require substantial investments and innovations, especially in energy management, smart grids, and AI-driven optimization.

Given these circumstances, it is clear that Czech manufacturing enterprises face an urgent need for comprehensive transformation that links digital innovation with sustainability principles. Sustainable digital transformation represents a strategic response, involving the deployment of advanced information systems, automation, and AI, as well as measures to reduce the environmental footprint of production. Only through such dual transformation can Czech industry enhance performance, resilience, and meet rising regulatory and customer demands for sustainable operations.

This article analyzes global trends in digital transformation in manufacturing from a sustainability perspective and examines their consequences for Czech industrial companies in the context of the ongoing Fourth Industrial Revolution.

2. Literature Review

2.1 The Impact of Information Systems and AI on Firm Performance

The adoption of advanced information systems (IS) and artificial intelligence (AI) technologies has been recognized as a primary driver of performance growth in manufacturing enterprises in recent years. Research consistently demonstrates positive effects of these technologies on labor productivity, process efficiency, and innovation capacity (Blichfeldt & Faullant, 2021; Zhang et al., 2023; Gastaldi et al., 2022). Modern IS support improved production planning, monitoring, and real-time control, while AI enables predictive maintenance, automated decision-making, and advanced data analytics (Mohamed et al., 2022; Tortorella et al., 2022; Bai et al., 2022).

The introduction of IS and AI also facilitates faster innovation and greater flexibility. Enterprises can better personalize products, respond to shifts in demand, and shorten innovation cycles (Chirumalla, 2021; Enrique et al., 2022). However, the benefits differ significantly between larger and smaller firms. Larger companies are more likely to possess advanced data infrastructures, strategic leadership, and better access to skilled employees, allowing them to realize a faster return on investment (Kubickova et al., 2021; Vlachos et al., 2023).

Recent studies have expanded the application of information systems and decision-support models beyond manufacturing, demonstrating their role in tourism, healthcare, and media ecosystems, investment areas (Peternel & Bukvič, 2024). Gavurova et al. (2025) highlight the socio-economic impact of digital transformation in tourism, introducing a hybrid decision-support model that enhances regional competitiveness. Complementary research by Gavurova and Polishchuk (2025) employs fuzzy set theory to design travel planning systems for people with disabilities, showing how digital tools can foster inclusivity. In parallel, Moravec et al. (2025) investigate algorithmic personalization, emphasizing both its potential for efficiency and the risks associated with digital literacy gaps. Healthcare applications have also been explored: Smolanka et al. (2024) evaluate the integration of information technologies in hospitals, while Gavurova, Smolanka, and Polishchuk (2024) propose an intellectual model for managing patient trust in medical staff. Moreover, studies in media and regional development contexts demonstrate how advanced IS can inform policy and investment decisions - such as assessing automated news content for media literacy (Gavurova et al., 2024) and evaluating large-scale tourism infrastructure projects (Skare, Gavurova & Polishchuk, 2023). Collectively, these findings illustrate the versatility of IS and AI-driven decision models, extending their benefits from firm-level efficiency to societal, healthcare, and regional outcomes.

2.2 Barriers to Implementation: Human, Organizational, and Technological Challenges

The successful implementation of IS and AI is not automatic and faces multiple barriers, which can be categorized as human, organizational, and technological. *Human barriers* include resistance to change, low digital literacy, insufficient motivation for further training, and limited awareness of the benefits of digitalization (Chauhan et al., 2021; Gastaldi et al., 2022). Frequently, there is also a lack of leadership support, vision, or willingness to invest in employee development (Kubickova et al., 2021; Bhatia & Kumar, 2022; Stoyanova & Angelova, 2024). *Organizational barriers* involve rigid structures, isolation of IT from operations, and the absence of coordination between management levels (Amaral & Peças, 2021; Enrique et al., 2022; Erboz et al., 2022). *Technological barriers* stem from inadequate infrastructure, poor data quality, lack of standards, and complications integrating new and legacy systems (Dhirani et al., 2021; Alabadi et al., 2022). In the Czech context, a conservative management approach and low trust in data sharing across supply chains also play a significant role (Chauhan et al., 2021; Amaral & Peças, 2021; Pfaff, 2023).

2.3 The Role of Leadership, Culture, and Digital Skills

Previous authors agree that technological maturity alone does not guarantee the success of digital transformation. Leadership is a key factor—the ability to create a digital vision, foster trust, and guide change (Adebanjo et al., 2023; Gastaldi et al., 2022). Successful adopters invest in the development of digital skills at all organizational levels, from operators to managers (Bhatia & Kumar, 2022; Lai et al., 2023), and build a culture of openness, collaboration, and data-driven learning (Chirumalla, 2021; Virmani et al., 2023). The ability to connect technological advancement with human factors is one of the main determinants of long-term success (Enrique et al., 2022; Ali & Johl, 2022).

2.4 Digitalization and Sustainability

Modern IS and AI are increasingly important for environmental sustainability and green innovation. Digital tools enable real-time monitoring and optimization of energy, material, and emissions (Favi et al., 2022; Lai et al., 2023; Ye et al., 2023). They are especially relevant in green supply chain management, circular economy practices, predictive maintenance, and sustainable product design (Khan et al., 2021; Song et al., 2022; Torrent-Sellens et al., 2023; Bag et al., 2023). Empirical studies confirm that firms investing in digital green solutions achieve both environmental and economic benefits – such as lower energy consumption, higher recycling rates, and improved resource efficiency (Karmaker et al., 2023; Asif et al., 2024). Such investments also enhance reputation and help enterprises meet stricter regulatory and customer demands.

2.5 Research Gaps

Despite rapid research development in IS/AI in manufacturing, several important gaps persist, especially in the Central and Eastern European context:

- Lack of case studies reflecting the specificities of post-transformation economies (Kubickova et al., 2021; Amaral & Peças, 2021).

- Absence of localized implementation frameworks adapted to the needs of Czech industry (Adebanjo et al., 2023; Yu et al., 2021).
- Limited quantitative evidence of real impacts—qualitative or declarative approaches still dominate (Ghobakhloo et al., 2024; Zhang et al., 2023).
- Fragmented treatment of digitalization and sustainability—most studies address economic, technological, and environmental aspects separately, without a systemic perspective (Kedir & Hall, 2021; Mohamed et al., 2022; Bag et al., 2023).

These findings point to several important avenues for future progress, including the development of localized implementation frameworks, greater use of quantitative research methods, and a stronger focus on the practical needs and challenges of Central European manufacturing enterprises.

3. Methodology

This study is based on a systematic literature review designed to analyze the relationship between digital transformation – particularly the implementation of information systems (IS) and artificial intelligence (AI) – and firm performance in the manufacturing sector. The review aimed to map the current state of scientific knowledge, identify key trends, research approaches, documented benefits and barriers to implementation.

3.1 Search Strategy

The literature review was conducted using the Web of Science (WoS) database, employing the Advanced Search Query Builder to cover the core topics of advanced AI, firm performance, the manufacturing sector, and digital technology adoption.

3.2 Selection and Filtering Criteria

An initial pool of 220 scientific articles was collected and filtered according to the following criteria:

- Publication period: 2020–2025
- Document type: Peer-reviewed articles and review articles
- Research fields: Engineering (industrial, manufacturing, multidisciplinary), economics and management, information technology, and related technical disciplines
- Language: English only
- Indexing: SCI-EXPANDED, SSCI, ESCI

3.3 Relevance Assessment and Final Sample

Each article was evaluated using a four-level relevance scale:

- 3: High relevance (direct connection to the research aim, e.g., empirical studies on the impact of AI/IS on manufacturing firm performance)
- 2: Medium relevance (partial thematic overlap, e.g., studies on technology adoption or broader digitalization impacts)
- 1: Low relevance (marginal relation to the topic)
- 0: Irrelevant (outside the research scope)

Additionally, a quantitative metric called "article value" was calculated as:

Article value = Number of citations + (Relevance × 10)

Only articles with a value ≥ 30 and at least medium relevance were included in the final sample. This process yielded 85 full-text articles that met both qualitative and quantitative requirements.

3.4 Statistical and Thematic Distribution

The majority of selected publications were from the last four years, reflecting the dynamism of research in this field:

- 2021: 24 articles
- 2022: 28 articles
- 2023: 23 articles
- 2024: 13 articles

Thematically, the articles covered digital transformation in manufacturing, the impact of IS/AI on productivity, change management and human factors, implementation barriers, green innovations, circular economy, smart manufacturing, and the integration of Lean and Industry 4.0. Geographically, the sample included studies from China, India, the United Kingdom, the United States, Italy, Germany, France, Spain, and Australia, reflecting broad international interest and enabling comparative interpretation across diverse economic and cultural contexts.

4. Findings and Discussion

Recent empirical research in Central and Eastern Europe further supports the crucial role of digital transformation and Industry 4.0 in improving firm performance and advancing sustainability outcomes. For instance, Krulický et al. (2024) demonstrate that the adoption of Industry 4.0 technologies among Czech manufacturing companies leads to significant increases in process efficiency and resource optimization, particularly through the reduction of waste and energy consumption. These results align with findings from Grenčíková et al. (2021), who emphasize that digitalization and automation helped Slovak enterprises increase their resilience and adaptability during the Covid-19 pandemic, thereby supporting business continuity in turbulent environments.

However, several studies highlight that the success of digital transformation is not determined by technology adoption alone. Tang and Zhou (2025) argue that unlocking the growth potential of underused resources within companies depends both on digital transformation and on robust decision-making capabilities at the managerial level. Importantly, a growing number of authors directly link digital transformation to sustainability performance. Burinskienė et al. (2025) and Peclinovský et al. (2024) provide empirical evidence that investments in digital technologies and Industry 4.0 lead to enhanced environmental outcomes, such as improved resource efficiency and reduced emissions in supply chains. These findings confirm that the integration of digitalization and sustainability is a key pathway for industrial enterprises seeking to achieve long-term competitiveness and resilience in a rapidly changing environment.

Nonetheless, as Talíř and Chytilová (2024) observe, digitalization alone may not guarantee immediate financial improvements, especially in crisis situations. This underscores the need for holistic strategies that combine technology, human capital development, and organizational change. The lessons drawn from these recent studies reinforce the relevance and urgency of developing context-specific and localized frameworks to maximize the benefits of digital transformation in Central and Eastern Europe.

4.1 Key Drivers of Successful Digital Transformation

Multiple authors confirm that the successful and sustainable digital transformation of manufacturing enterprises is determined by four mutually reinforcing domains: technological infrastructure, human competencies, organizational culture, and strategic sustainability orientation (Blichfeldt & Faullant, 2021; Bhatia & Kumar, 2022; Virmani et al., 2023; Bag et al., 2023). These areas serve as the axes of transformational readiness and form the basis for a practical framework for both businesses and policymakers.

Technological Enablers

Key technological factors include the availability and integration of IS/AI systems, data quality, interoperability of systems, and the use of cloud platforms, IoT, and predictive analytics (Blichfeldt & Faullant, 2021; Matin et al., 2023; Duan & Xu, 2024). Firms with robust technological foundations are better positioned to achieve productivity gains and rapid innovation.

Competencies and Human Capital

Developing digital skills at all organizational levels – facilitated through internal training, external education, and partnerships with academic institutions – is crucial. The ability to collaborate across IT and operations, continuous learning, and upskilling are repeatedly highlighted as essential for transformation success (Chirumalla, 2021; Bhatia & Kumar, 2022; Lai et al., 2023).

Organizational Culture and Change Management

An open, innovation-oriented culture, participative leadership, transparent communication, and the active involvement of employees in digital initiatives are strong enablers of long-term success (Virmani et al., 2023; Gastaldi et al., 2022; Pfaff, 2023). Change management practices must prioritize employee engagement and trust in technology.

Sustainability as a Strategic Principle

Integrating environmental management, green supply chain practices, and circular economy principles is becoming a standard part of digital transformation strategies (Bag et al., 2023; Torrent-Sellens et al., 2023; Asif et al., 2024). Successful companies systematically include environmental metrics in their KPIs and leverage AI to optimize resource consumption and minimize emissions.

4.2 Barriers and Challenges

Despite the potential benefits, manufacturing enterprises face a range of persistent barriers:

- Human barriers: Resistance to change, low digital literacy, and limited motivation for further education impede progress (Chauhan et al., 2021; Gastaldi et al., 2022).
- Organizational barriers: Rigid hierarchies, poor integration between IT and production, and lack of cross-functional coordination are common obstacles (Amaral & Peças, 2021; Enrique et al., 2022; Erboz et al., 2022).
- Technological barriers: Legacy infrastructure, inadequate data quality, lack of interoperability, and integration challenges complicate the deployment of new systems (Dhirani et al., 2021; Alabadi et al., 2022).
- In the Czech context, conservative leadership and a lack of trust in data sharing across value chains present additional obstacles (Chauhan et al., 2021; Amaral & Peças, 2021; Pfaff, 2023).

4.3 The Interplay Between Digitalization and Sustainability

Modern IS and AI technologies are key enablers not only for operational performance but also for environmental sustainability. Digital tools allow for real-time monitoring and optimization of energy use, material flows, and emissions, contributing to both ecological and economic benefits (Favi et al., 2022; Lai et al., 2023; Ye et al., 2023). Green supply chain management, circular economy practices, and AI-driven predictive maintenance are examples of how digitalization supports sustainability goals (Khan et al., 2021; Song et al., 2022; Torrent-Sellens et al., 2023; Bag et al., 2023).

4.4 Future Directions

According to recent authors, there are several areas that warrant further exploration, particularly in the context of Central and Eastern European manufacturing:

- Lack of contextualized case studies: There is a shortage of empirical studies reflecting the unique conditions of post-transformation economies (Kubickova et al., 2021; Amaral & Peças, 2021).
- Absence of localized implementation frameworks: Adapted approaches are needed for the specific challenges of Czech industry, including company size, organizational structure, and culture (Yu et al., 2021; Adebajo et al., 2023).
- Need for more quantitative evidence: Much of the current research relies on qualitative or declarative findings, emphasizing the need for robust quantitative studies (Zhang et al., 2023; Ghobakhloo et al., 2024).
- Systemic integration of digitalization and sustainability: Future research should address these areas in a holistic manner, rather than as separate domains (Kedir & Hall, 2021; Mohamed et al., 2022; Bag et al., 2023).

4.5 Four-dimensional Assessment Framework for Sustainable Digital Transformation

Based on the synthesis of recent studies, a **four-dimensional assessment framework** is proposed to guide manufacturing enterprises and policymakers in planning and implementing sustainable digital transformation initiatives. The framework encompasses four key domains – **technology, competencies, culture, and sustainability** – which jointly determine transformational readiness and long-term impact.

Table 1. Four-dimensional assessment framework

Domain	Key Questions for Assessment
Technology	Are advanced IS/AI systems implemented? Are they interoperable? Is there access to relevant data and analytics?
Competencies	Does the organization possess the necessary digital skills for new technologies? Are there ongoing investments in employee development?
Culture	Does the organizational culture support innovation and collaboration? Is leadership actively driving and communicating the transformation?
Sustainability	Are environmental measures in place? Are energy consumption, CO ₂ emissions, and waste systematically monitored and managed? Is green tech utilized?

This framework can be utilized for **self-assessment** within organizations (e.g., via maturity matrices) or as a **strategic management tool** for driving change. Its application allows enterprises to evaluate not only technical readiness but also the softer organizational factors that are critical for the long-term sustainability of digital transformation.

By integrating these four domains, companies are better equipped to turn isolated digital initiatives into comprehensive, systemic change – thereby enhancing both economic performance and environmental resilience.

5. Conclusions

This article has explored the trends, barriers, and opportunities of sustainable digital transformation in the manufacturing sector, with a particular focus on the Czech context. The systematic review of 85 peer-reviewed articles confirms that advanced information systems and artificial intelligence have significant potential to improve organizational performance through automation, predictive analytics, process optimization, and more efficient use of resources. However, the success and sustainability of digital transformation depend on the synergistic interaction of four critical domains: technology, competencies, organizational culture, and strategic sustainability orientation.

Integrating these domains allows enterprises to transform fragmented digital initiatives into deeper structural change, leading to long-term gains in both performance and environmental impact. The proposed four-dimensional assessment framework offers a practical tool for organizations and policymakers to assess digital maturity and prioritize actions for sustainable transformation.

For Czech manufacturing, this agenda is especially urgent due to labor shortages, rising costs, decarbonization pressures, and evolving customer demands. At the same time, there remains a lack of localized frameworks, empirical evidence, and validated best practices tailored to Central and Eastern European industry. Addressing these gaps represents a significant opportunity for both researchers and practitioners. This article is based solely on a systematic literature review and conceptual synthesis. It does not provide primary empirical data; the proposed framework therefore requires empirical validation – such as through case studies, surveys, or action research within industrial enterprises.

Several promising avenues for further research emerge from this review:

- Quantitative assessment of the impact of IS/AI adoption on sustainability metrics (e.g., energy consumption, carbon footprint, recyclability).
- Development and testing of adaptive and scalable frameworks for small and medium-sized enterprises.
- Exploration of the roles of leadership and organizational culture in digital transformation across different types of companies.
- Integration of ethical and security aspects (e.g., AI governance, cybersecurity) into frameworks for sustainable digitalization.

Overall, digital transformation and sustainability are not separate challenges, but interconnected and mutually reinforcing. Only those companies that can align technological progress with competence development,

innovative culture, and a strategic approach to sustainability will succeed in the dynamic environment of the 21st-century global economy.

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