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Strategic Framework for Accelerating Industry 4.0 Implementation in Romanian Manufacturing SMEs

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Abstract
Industry 4.0 implies the automation and digital transformation of traditional manufacturing processes through smart technologies, namely Internet of Things, artificial intelligence, big data analytics and cyber-physical systems. This paper presents the current state, challenges and potential solutions for increasing Industry 4.0 adoption by the Romanian manufacturing companies. The research methodology involved interviewing Romanian small and medium-sized enterprises (SMEs) managers and, based on their opinion, a strategic framework was designed to accelerate Industry 4.0 implementation, with the goal of increasing their productivity and competitiveness. The results identified challenges for Industry 4.0 implementation, including financial constraints, workforce skill gaps and technical infrastructure limitations. Additionally, the study highlighted solutions to overcome these challenges and acceleration strategies. We concluded that a successful Industry 4.0 implementation in Romanian manufacturing SMEs requires a coordinated approach across multiple dimensions: technological infrastructure, human capital, financial instruments, innovation ecosystem, regulatory framework and governance models.

Keywords
industry 4.0, implementation, Romanian manufacturing companies, challenges, SMEs

1. Introduction

Industry 4.0 represents a fundamental transformation in manufacturing advanced technologies that enable smart, connected, and autonomous production systems. The objective of integrating these technologies into the industrial setup is to maximize automation, productivity, and operational efficiency [1].

Industry 4.0 is driven by several cutting-edge technologies, including [2 ÷ 5]:

- Internet of Things (IoT), which facilitates real-time data collection and process optimization;
- Artificial Intelligence (AI) and Machine Learning (ML) that enables predictive maintenance, quality control and process automation;
- Big Data and Analytics that enhances decision-making by analysing vast amounts of industrial data;
- Cyber-Physical Systems (CPS), which integrates digital and physical production environments;
- Robotics and Automation, which improves efficiency, accuracy, and production speed;
- Additive Manufacturing (3D Printing) that allows for rapid prototyping and customized production;
- Cloud Computing, which supports data storage, collaboration, and scalability.

These cutting-edge technologies are facilitated by the integration of computer-assisted systems within industrial companies to support their production processes. More flexibility, shorter production cycles, quicker reactions to shifting market demands and better control and accuracy in production processes are all made possible by the use of sophisticated manufacturing technologies to monitor and regulate industrial activities [6].

The integration of Industry 4.0 is increasingly important for the industrial companies' competitiveness. However, there are some challenges that occur during Industry 4.0 implementation [2].

Since smart manufacturing systems need more autonomy and social capabilities—both necessary for self-organized systems—an *intelligent decision-making and negotiation mechanism* is one crucial component. Another major challenge is *high-speed IWN protocols*, since existing Industrial Wireless Networks (IWN) do not provide adequate bandwidth for large-scale data transfer and intensive

communication. Nevertheless, IWN remains superior to wired networks in manufacturing environments [7].

Additionally, m*anufacturing-specific Big Data and Analytics* pose significant difficulties in ensuring the quality and integrity of data collected from manufacturing systems. The diversity of data annotations and the integration of various data repositories with different semantics create challenges for advanced data analytics [8].

Regarding *system modeling and analysis*, developing appropriate control models and reducing complex dynamic equations require manufacturing systems to be structured as self-organized systems. However, research in this area is still ongoing, particularly for complex systems [7].

Another critical concern is c*ybersecurity*, as the improved level of connectivity and widespread use of standardized communication protocols expose industrial systems and production lines to major cybersecurity threats, necessitating enhanced protection measures [2].

Furthermore, *modular and flexible physical components* are essential for optimizing manufacturing processes. Equipment used for machining or testing should be grouped efficiently to enable distributed decision-making. Therefore, developing modular and smart conveying units capable of dynamically reconfiguring production routes is crucial [7].

Lastly, *investment challenges* remain a significant barrier to the adoption of Industry 4.0, particularly for small and medium-sized enterprises (SMEs). Many companies struggle to afford advanced digital technologies. Implementing all principles of Industry 4.0 requires substantial financial resources, making it a considerable investment challenge for many industries [2, 9].

Also, the adoption of Industry 4.0 is often hindered by a lack of skilled workforce, as there is a shortage of professionals trained in data analytics and automation, along with resistance to change, as some businesses remain hesitant to shift from traditional manufacturing methods.

The aim of the presented paper is to present the challenges the Romanian manufacturing companies face for Industry 4.0 implementation in order to provide a strategic framework for accelerating its development.

2. Adoption of Industry 4.0 in Romanian Manufacturing Companies

Romania's manufacturing sector contributed in 2023 on average of 12.62% to the country's GDP, making it an important component of the economy [10]. The evolution of the manufacturing sector share in the GDP of Romania (2020-2023) is presented in Figure 1. As it can be seen, the share gradually decreased to 12.6% in 2023, which highlights potential challenges, such as industrial competitiveness and investment in technology. Compared to the European Union share (which was 15% in 2023, according World Bank Group [11]), Romania had a lower share that implies the need to enhance productivity, innovation and competitiveness. EU's higher and more stable manufacturing contribution highlights the importance of advanced manufacturing strategies and continuous technological upgrades.

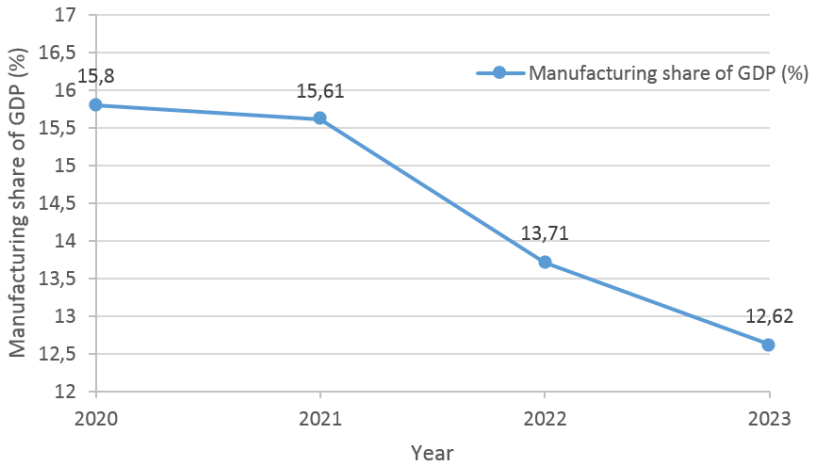

Fig. 1. Evolution of Romania's value added by the manufacturing sector as percent of GDP (2020-2023) [10]

Traditional manufacturing methods still dominate, with varying levels of automation and digital integration across different industries. However, Romanian manufacturing companies have begun implementing Industry 4.0 technologies, particularly in the automotive, aerospace and electronics industries. Leading firms are investing in automation, IoT-based monitoring systems and AI-driven analytics to improve efficiency and reduce costs.

According to Găvruș et al., [12], a 2023 study conducted on 260 Romanian enterprises operating in the manufacturing engineering industry revealed that a significant percentage (96.9%) of Romanian manufacturing companies had adopted some concepts of Industry 4.0. Relatively few Industry 4.0 principles are currently being implemented, with most scores ranging between 3 and 4 on ordinal scales, where 5 represents full implementation and 1 indicates no implementation at all.

According to the study, small and micro businesses have recorded notable scores when it comes to apply the concepts of Industry 4.0 because of their flexibility and more effective employee communication compared to large and medium-sized companies [12]. In terms of advantages, companies agreed that productivity and working conditions were especially improved by applying Industry 4.0 principles. These advantages, which included better working conditions, higher employee motivation, greater product quality and increased productivity, led to increased scores in SMEs [12].

Previous studies [13 ÷ 15] emphasized the importance of addressing small and medium-sized enterprises separately from large organizations when implementing Industry 4.0 strategies.

According to [16], SMEs encounter more challenges compared to large companies due to poorly formalized processes, less advanced IT infrastructure and limited economic resources.

Starting from previous findings, the presented research aimed to identify the main challenges that Romanian SMEs encounter in implementing Industry 4.0 principles, solutions and acceleration strategies. The used research method was the survey, based on interviewing Romanian SMEs managers in the industrial manufacturing sector.

The interview guide was divided in three sections. The first section aimed to obtain information about the current status of Industry 4.0 implementation. Following this, the guide addressed the challenges that companies face when implementing Industry 4.0, in order to understand the factors limiting the adoption of these technologies and to explore the solutions and strategies that companies have used to overcome these challenges. Finally, the interview addressed questions regarding the company's long-term vision for digitalization and transformation and the elements that could accelerate the implementation of Industry 4.0 in the future.

Researchers conducted the interviews with 3 managers from small and medium-sized manufacturing companies from Romania: a manufacturer of metal components for the automotive industry (M1), a manufacturer of electrical and electronic components (M2) and a manufacturer of automated equipment (M3). The interviews revealed several important insights.

The companies demonstrate varying levels of Industry 4.0 adoption. M1 achieved moderate implementation, focusing primarily on automation and quality control systems essential for automotive industry compliance. M2 presented an increased level of digital maturity, integrating IoT sensors throughout their production line and using advanced testing equipment with data analytics capabilities. M3 maintained a mixed environment where they produce advanced automation solutions for clients while their own production processes remain partially digitalized. The company uses 3D printing for prototyping and CAD/CAM systems.

The research allowed a deeper exploration of the barriers these companies face when attempting to adopt Industry 4.0 technologies, as well as potential solutions based on the managers' practical experience.

The managers recognized the potential benefits of Industry 4.0 but felt constrained by limited financial resources for significant technological investments. This result is consistent with papers [2] and [9] that pointed out that implementing Industry 4.0 requires substantial financial resources. According to [17 ÷ 19] the lack of financial resources could limit the success of digitalization, overall for SMEs.

Thus, M1 considered that the high initial investment required for automation systems and the long Return on Investment periods were challenging for a company their size. M2 faced issues with ongoing costs related to software licenses and cloud services, though they have managed to use EU funding for

initial implementations. M3 considered that it is difficult to balance investing in their own digitalization while maintaining competitive pricing for their automation solutions.

The interviews revealed complex workforce-related challenges. M1 reported difficulty in finding and retaining qualified technicians capable of maintaining advanced manufacturing equipment, noting that younger workers often preferred opportunities in larger cities or abroad. M2 had invested significantly in training programs but the technological continuous change requires continuous upskilling. M3 faced unique challenges, as their workforce needed both traditional manufacturing skills and advanced programming capabilities. The lack of skilled personnel was also noted as a significant obstacle for Industry 4.0 implementation in papers [19 ÷ 21].

Technical infrastructure limitations emerged as a significant concern. M1 operates in an older industrial facility that requires substantial modifications to support modern networking and automation systems. M2 faces challenges with integrating new systems with legacy equipment, particularly in data collection and standardization. M3 reported adequate infrastructure but struggles with cybersecurity implementation across their network. Thus, a common obstacle found was the difficulty in integrating new systems with existing infrastructure, result consistent with studies [22] and [23].

However, the managers' perspectives indicated that, while the path to Industry 4.0 presents significant challenges, it is viewed as essential for maintaining competitiveness in the market. So, the companies have used some solutions and strategies to overcome the encountered challenges and barriers. M1 has adopted a step-by-step approach to overcoming implementation challenges. The company has established a dedicated digitalization team that includes both experienced engineers and younger technical specialists. They have implemented a mentoring system where senior staff work closely with junior employees to transfer knowledge about both traditional manufacturing processes and new digital technologies. To address financial constraints, they have developed a phased implementation plan that prioritizes technologies with the most immediate impact on quality and productivity. M2 created a formal digital transformation roadmap with clear milestones and metrics. They have used EU funding for several projects. The company also implemented a training program where employees can earn certifications in different Industry 4.0 technologies. M3 has used its dual role as a manufacturer and automation provider to create innovative solutions. They have transformed their factory into a "living lab" where they test and improve automation solutions before offering them to clients. This approach helps train the staff on new technologies while simultaneously developing market-ready products.

All three managers emphasized the critical importance of financial support, but their specific needs varied significantly. M1 highlighted the need for direct investment support, particularly for expensive automation equipment required by automotive industry standards. M2 pointed out that many Industry 4.0 technologies involve subscription-based services and regular upgrades, requiring sustained financial commitment. They suggested tax incentives for companies investing in digital technologies and skills development. M3 focused on the need for technical support and knowledge transfer programs. While financial support is important, they emphasized that access to expertise and technical resources is equally crucial. They suggested creating regional competency centers where SMEs could access advanced technologies and expertise.

The managers' vision for the next five years is optimistic. M1 plans to achieve full automation of their main production lines, including implementing advanced robotic and developing predictive maintenance capabilities. M2 aims to obtain AI-driven quality control, to expand the use of collaborative robots and to develop advanced analytics capabilities. M3 aims to create a technology integration hub, leveraging their experience to help other manufacturers adopt Industry 4.0 technologies. Their internal goals include achieving full digital integration of their design, production and testing processes while expanding their capability to develop custom automation solutions.

Several critical factors that could accelerate Industry 4.0 implementation were identified. All three managers agreed that increasing competition would continue to drive digital transformation. M1 specifically noted that automotive industry requirements are becoming more stringent, necessitating higher levels of automation and quality control. Also, the managers emphasized that improving the

technical education system and developing more practical training programs would be crucial. M2 suggested that creating specialized Industry 4.0 training centers could help address the skills gap.

There was consensus that more robust government support, including both financial incentives and policy frameworks, would be essential. M3 particularly emphasized the need for policies that encourage technology transfer and collaboration between larger companies and SMEs.

The managers offered several valuable recommendations for accelerating Industry 4.0 implementation in Romanian manufacturing companies. M1 emphasized the importance of creating industry-specific implementation guidelines and best practices, noting that generic digital transformation advice often fails to address sector-specific challenges. M2 recommended developing regional innovation clusters where companies could share resources and expertise, suggesting this could make advanced technologies more accessible to SMEs. M3 pointed the importance of maintaining flexibility in digital transformation strategies, arguing that companies need to be able to adapt their approaches as technologies and market conditions evolve.

The findings suggest that successful Industry 4.0 implementation in Romanian SMEs requires a coordinated approach involving government support, educational system alignment, and strong industry collaboration.

3. A Strategic Framework for Accelerating Industry 4.0 Implementation in Romanian Manufacturing Companies

An increase of the implementation level of the Industry 4.0 technologies in Romanian manufacturing, companies will lead to an increase in productivity, competitiveness and economic resilience.

Based on the challenges, critical factors and recommendations proposed by the interview participants, a strategic framework was designed to accelerate Industry 4.0 implementation across Romanian manufacturing companies, with the goal of increasing their productivity and competitiveness.

The strategic framework, presented in Figure 2, provides a comprehensive roadmap for accelerating Industry 4.0 implementation, bringing together all stakeholders in a coordinated effort.

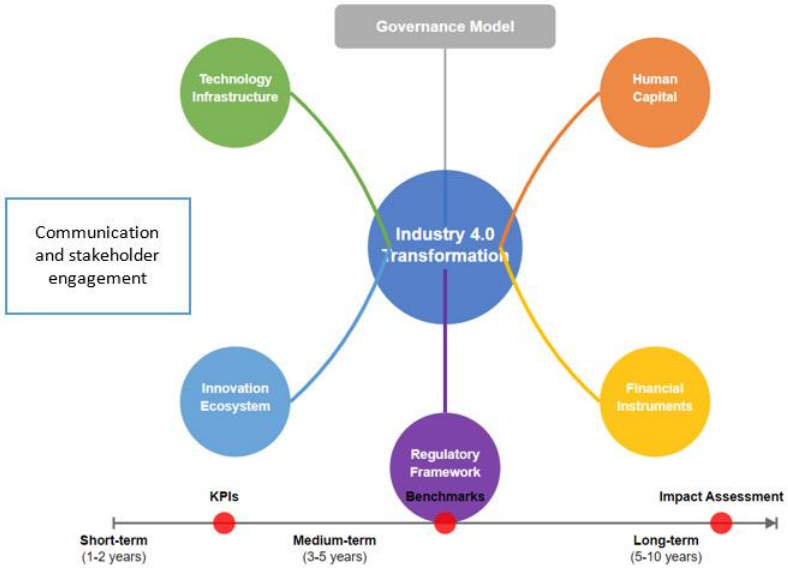

Fig. 2. Strategic framework for accelerating Industry 4.0 implementation

The framework presents six dimensions that interact to enable *Industry 4.0 transformation*: technology infrastructure, human capital, financial instruments, innovation ecosystem, regulatory framework and governance model.

Technology infrastructure represents the foundational technical systems, networks, and hardware needed to support digital transformation. This aligns with what the Romanian managers interviewed, which identified as a critical challenge, particularly for M1 who operates in an older facility requiring significant infrastructure updates.

Human capital represents the crucial role of workforce development and skills - a major concern highlighted by all three Romanian managers, especially regarding finding and retaining qualified personnel capable of working with advanced technologies.

The financial instruments component reflects the financial support required for industrial transformation. This was particularly emphasized by M2, who successfully leveraged EU funding, while M1 and M3 noted significant financial constraints.

Innovation ecosystem represents the network of partnerships, research collaboration and knowledge sharing. It highlights the importance of innovation for industrial development and progress.

The regulatory framework represents the necessary regulations and standards to guide transformation.

The governance model coordinates the entire transformation process, ensuring that decisions and actions across all areas are consistent with organizational objectives and industry standards.

A continuous communication is necessary throughout the implementation process, ensuring that all stakeholders are consulted and involved.

Industry 4.0 transformation can be considered into three phases:

- Short-term (1-2 years): with focus on establishing key performance indicators (KPIs) and initial implementation;
- Medium-term (3-5 years): the development of benchmarks to assess maturity and compliance;
- Long-term (5-10 years): comprehensive impact assessment of the transformation and strategic evaluation.

This phased approach mirrors how the Romanian companies are implementing their transformations – M1 as a step-by-step approach, M2 as a comprehensive roadmap and M3 as a modular implementation strategy.

The presented framework illustrates that successful Industry 4.0 transformation requires a balanced and synchronized development of all dimensions. The challenges faced by the Romanian SME managers demonstrate that weaknesses in any of these areas can hinder overall progress. For example, even when companies have strong technological capabilities, like M3, limitations in other areas such as financial instruments or human capital can slow transformation.

The connection between the dimensions explains why the managers emphasized the need for coordinated support across multiple areas, including government funding, educational partnerships, technical assistance and regulatory frameworks. This perspective underscores that Industry 4.0 implementation requires more than just technological investment – it demands the simultaneous advancement of all these dimensions to ensure a sustainable and effective transformation.

4. Conclusions

For Romanian manufacturing companies to be competitive in the global economy, the transition to Industry 4.0 is essential. The study provided valuable insights that help understand both the challenges and potential solutions for increasing Industry 4.0 adoption in the SME sector. The provided answers revealed that Romanian manufacturing SMEs are actively engaging with Industry 4.0 transformation, but they are facing significant challenges. Financial constraints remain the primary barrier, but workforce development and technical infrastructure also present substantial challenges. The companies demonstrate resilience and creativity in developing solutions, particularly through partnerships and staged implementation approaches.

The varying levels of implementation across the three companies reflect both sector-specific requirements and individual company capabilities.

Our research contributes to both theoretical understanding and practical implementation by establishing that successful Industry 4.0 transformation extends beyond technological adoption.

The findings suggest that successful Industry 4.0 implementation in Romanian manufacturing SMEs requires a coordinated approach across multiple dimensions: technological infrastructure, human capital, financial instruments, innovation ecosystem, regulatory framework, and governance models. This conclusion is particularly relevant for emerging economies where SMEs must balance resource constraints with the imperative to modernize.

The temporal analysis reveals that Industry 4.0 implementation is an evolutionary process requiring sustained commitment and adaptability. This understanding has significant implications for policymakers and business leaders in developing support mechanisms for SME digital transformation.

Future studies will focus on measuring the effects of different support systems and examining the long-term efficacy of various implementation techniques across a range of manufacturing industries.

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