sciendo

Management Systems in Production Engineering

2025, Volume 33, Issue 1, pp. 144-162

Date of submission of the article to the Editor: 08/2024
Date of acceptance of the article by the Editor: 01/2025

DOI 10.2478/mspe-2025-0015

SUSTAINABLE DEVELOPMENT AND TECHNOLOGICAL ADVANCEMENTS IN INDUSTRY 4.0: OVERCOMING BARRIERS IN SME SECTOR INTEGRATION

Manuela Ingaldi, Robert Ulewicz
Czestochowa University of Technology

Abstract:
The advent of Industry 4.0 has introduced transformative opportunities for the SME sector, particularly in enhancing operational efficiency, fostering sustainability, and enabling digital connectivity within manufacturing processes. This study examines key barriers faced by SMEs in adopting Industry 4.0 technologies, including high initial investments, skills gaps in digital competencies, and logistical limitations in production infrastructure. It explores a collaborative platform model that facilitates resource sharing among SMEs to reduce individual costs, optimize technology access, and improve competency development. Findings highlight that while shared platforms can successfully mitigate certain financial and operational barriers, the scalability of such models faces limitations due to stakeholder interests and infrastructure constraints. This research provides insights into the critical role of technological advancements and sustainable practices in supporting SMEs' Industry 4.0 transition and emphasizes the need for adaptive strategies to maintain integration viability as production demands evolve.

Key words: Industry 4.0, SME integration, digital transformation, collaborative platforms, technology adoption barriers

INTRODUCTION

The development of Industry 4.0 has introduced transformative opportunities for small and medium-sized enterprises (SMEs), particularly in enhancing operational efficiency, fostering sustainability, and enabling digital connectivity within manufacturing processes. The introduction of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics facilitates automation and improved process coordination, contributing to greater production flexibility, resource savings, and more effective energy management. For SMEs, which constitute a significant part of the economy, adopting Industry 4.0 is crucial to maintaining competitiveness. However, this trans-formation also presents challenges related to financing, skills acquisition, and scaling these solutions to the realities of smaller organizations.

Nowadays, innovation and technological development are essential for modern enterprises, as they can increase operational efficiency, production flexibility or business profits. They are an indispensable part of the functioning in the enterprises. However, it should be emphasized that advances in digital transformation and growing interconnectedness pose new challenges for organizations, as Industry 4.0 is significantly changing products and production systems for projection, processes, operations and services, has created new opportunities, indicated new directions of development and new distribution channels [1, 2]. The concept is changing the way companies are managed, but also changing the jobs themselves by creating new business models. These new business models have a major impact on the industry itself and markets, but also on the product life cycle due to the new "improved" production process, which also increases the competitiveness of the company itself [3]. These new business models require employees to have a range of new competencies and skills, including digital literacy, data analysis, and communication skills. Soft skills, such as problem-solving, critical thinking, and adaptability, are also becoming increasingly important in the digital workplace.

The industrial transformation from the third to fourth generation has significantly affected sustainability. For this reason, various sectors are adopting Industry 4.0 technologies to improve their processes. Implementing Industry 4.0 technologies, such as automation, artificial intelligence, and the Internet of Things, can significantly improve productivity, efficiency, and quality in the production sector. Moreover, these technologies can contribute to sustainability by reducing waste, energy

© 2025 Author(s). This is an open access article licensed under the Creative Commons BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

consumption, and environmental impact [4, 5]. Sustainable technologies, which prioritize environmental and social responsibility, are a crucial aspect of Industry 4.0 technologies and innovations in the context of the Sustainable Development Goals (SDGs) [6]. As a result, the management of manufacturing enterprises is shifting towards a more sustainable and socially responsible approach, which is now considered a trendsetter in the industry.

Industry 4.0 refers to the fourth industrial revolution, which is characterized by the integration of advanced digital technologies into manufacturing and other industries. The impact of Industry 4.0 on sustainable development is the subject of research by many scientists [7, 8, 9, 10, 11, 12, 13, 14, 15]. They stated, among other things, that:

- Energy Efficiency: One of the main ways in which Industry 4.0 can promote sustainability is through increased energy efficiency. By using advanced sensors, automation, and data analytics, manufacturing plants can optimize their energy usage and reduce their carbon footprint.
- Waste Reduction: Industry 4.0 technologies can also help reduce waste in manufacturing processes. By using sensors and data analytics to monitor production processes, companies can identify areas where waste can be minimized or eliminated. This can reduce the amount of waste sent to landfills and improve resource efficiency.
- Circular Economy: Industry 4.0 can facilitate the transition towards a circular economy, where products are de-signed for reuse, repair, and recycling. By incorporating digital technologies such as the Internet of Things (IoT) and artificial intelligence (AI), companies can track the lifecycle of their products and identify opportunities for reusing or recycling materials.
- Sustainable Supply Chains: Industry 4.0 can also promote sustainability by enabling more sustainable supply chains. By using data analytics and AI, companies can optimize their supply chains for efficiency and sustain-ability. This can involve identifying suppliers with better environmental practices or reducing transportation emissions by optimizing delivery routes.

Renewable Energy Integration: Finally, Industry 4.0 can promote sustainability by facilitating the integration of renewable energy sources such as solar and wind power into the manufacturing process. By using advanced sensors and data analytics, manufacturing plants can optimize their energy usage to take advantage of renewable energy sources and reduce their reliance on fossil fuels.

The trends in business management strategies is moving toward technology platforms and digital innovation to pro-mote the internationalization of the industrial sector [16]. As industries become more interested in Industry 4.0 and the progressive increase in the co-benefits of such changes, as well as the unavailability of research in this topic, the concentration of research work in the business sector in this particular area is becoming more concentrated [17].

The IoT platform is a critical technology for Industry 4.0. Its multi-layered structure enables the easy provisioning, management and automation of connected devices within the Internet of Things (IoT). These platforms originated in the form of IoT middleware to serve as an intermediary between the hardware and application layers. Their main functions include collecting data from devices using different protocols and network topologies, remotely configuring and controlling of devices, managing devices and providing over-the-air firmware updates [18]. The author Chromjakova [19] highlights the importance of developing a communication platform that can connect machines, technologies, processes, information and material flow, thereby bridging the gap between the virtual information world with the real technological world. Furthermore, the author emphasizes the need to identify, establish and standardize a collaborative platform for a digitally con-trolled production process, flexible simulation of the production process, and a database containing information on the availability and performance parameters of technology production technologies.

Companies, implementing various types of Industry 4.0 solutions, can create industrial platforms that connect and coordinate the flow of information between company departments and external partners. The interest in platforms comes, among other things, from their potential to generate "network effects," which means that more complex and disruptive solutions can be developed by adding technology [20, 21].

Wang and others [22] argued that it is crucial to establish a collaborative innovation platform that facilitates for sharing and retrieving innovation information, gathering customer needs and related ideas, and making full use of external resources for innovation. Similarly, Chandio and co-authors [23] emphasize the need to build an innovation cooperation platform to realize effective convergence of innovation factors on the platform to achieve better cooperation for open innovation. Melenden and his friends [24] stated that a platform comprises both of "soft" and "hard" elements. An enterprise needs to build a collaboration platform to provide a virtual environment for open innovation. Innovators can express their suggestions and relative ideas for improving products and services on the forum. King and Grobbelaar [25], after Brenner [26] assert that while platforms are not a new concept, Industry 4.0 has changed them by reducing the need for physical infrastructure and assets.

Small and medium-sized enterprises (SMEs) are important targets for innovation implementation. They are the ones that need rapid changes in order to be able to improve the quality of manufactured products, increase production capacity or profit. Unfortunately, it is this group of enterprises that most often faces with various barriers to such changes, especially high costs. Their participation in various platforms bringing together similar manufacturers allows them to spread the costs among all participants and benefit from experience of each other.

One of the primary obstacles for SMEs in the digital transition is the high initial investment required for modern equipment and information technology, alongside the need to acquire specialists with digital and analytical

competencies. Consequently, the development of new collaborative models, such as resource-sharing platforms, is becoming essential. These platforms allow SMEs to share resources, exchange experience, and optimize technology access, enabling them to reduce individual costs, improve operational efficiency, and enhance access to advanced technologies.

However, a key challenge remains the scalability of these collaborative platforms. While resource and infrastructure sharing can reduce costs, increase production flexibility, and enhance operational efficiency for SMEs, limitations stemming from individual stakeholders' interests and infrastructural constraints may restrict the scalability of such solutions. Conflicts of interest, varying business needs, and limited infrastructure capacity can hinder the full utilization of collaborative platforms, especially as production demands rise.

Furthermore, regulatory and data security issues present additional barriers for SMEs seeking to adopt collaborative digital platforms. As more businesses share data and re-sources, ensuring compliance with data protection regulations, such as the GDPR in Europe, becomes increasingly challenging. SMEs often lack dedicated personnel for man-aging compliance, which can make them hesitant to fully engage in resource-sharing initiatives.

To address these barriers, policy support and incentive programs are vital. Government-backed funding schemes, tax incentives, and support for upskilling employees can significantly reduce the initial financial burden on SMEs, making it more feasible for them to invest in advanced digital tools. Additionally, establishing standardized guidelines for data sharing and security within these platforms can foster trust and make the transition to digital collaboration smoother for smaller businesses.

Ultimately, enhancing the scalability, security, and regulatory alignment of collaborative platforms will be crucial for SMEs to leverage innovation and remain competitive in an increasingly digital and interconnected market. This holistic approach can empower SMEs not only to overcome existing barriers but also to thrive in a rapidly evolving business land-scape.

This article explores how technological advancement and sustainable development can support the integration of SMEs into Industry 4.0, addressing barriers related to scalability and resource access. By examining collaborative plat-form models, the study emphasizes the need for flexible strategies to adapt Industry 4.0 technologies to the specific needs of SMEs and sustain integration viability in evolving production environments.

The paper presents research findings on the development model for manufacturing SMEs within the Industry 4.0 con-text, focusing on the main barriers these enterprises face. These challenges include high investment costs, the expense of purchasing advanced technology, and a shortage of workers skilled in Industry 4.0 competencies. The study pro-poses solutions, such as creating platforms for experience sharing, resource sharing, and personnel exchange, to mitigate these issues. By reducing individual costs and enhancing access to skilled workers and technology, SMEs can more feasibly adopt Industry 4.0 innovations.

The findings reveal that while these collaborative solutions were initially successful, increased demand for diverse metal products and production trends highlighted limitations in the shared infrastructure model. As production capacity constraints emerged, individual stakeholders found it challenging to scale operations while maintaining infrastructure accessibility. This led some participants to reconsider the shared model and eventually spin off into independent operations. The study also explores subcontracting as a potential growth strategy but identifies risks related to quality control and logistical complexities, which could affect flexibility and responsiveness to market changes.

This case study contributes to the scientific discourse on Industry 4.0 implementation in manufacturing, providing insights into the challenges and opportunities that arise as companies adopt new technologies and restructure their operations. The study highlights how Industry 4.0 can improve efficiency, reduce costs, and support sustainable growth, while also identifying areas for further research, particularly on the effectiveness of these models across different contexts.

Ultimately, this research enhances understanding of Indus-try 4.0's impact on manufacturing performance and offers valuable lessons for practitioners and policymakers striving to promote innovation and competitiveness in the manufacturing sector.

LITERATURE REVIEW

variety of ways to cut costs and make the best use of available resources. For example, organizations are looking for Lean system solutions to streamline their operations by eliminating what does not bring value to the customer, while increasing the efficiency of the production process [27].

In recent years, however, most manufacturing companies around the world have been trying to meet the demands of the fourth industrial revolution, called Industry 4.0. It is primarily associated with the digital transformation of individual company processes, especially the large-scale use of machine-to-machine (M2M) communications and Internet of Things (IoT) deployments to increase automation, communication and self-monitoring, including smart machines that can provide big data to analyze and diagnose problems with little human intervention [28, 29]. Such solutions would certainly help improve the efficiency of companies, especially in the manufacturing sphere. Ślusarczyk [3] indicated that the goal of Industry 4.0 is to achieve higher levels of operational efficiency and productivity, as well as higher levels of automation.

Authors [30] emphasized that technological advances in the 21st century have catalyzed an industrial revolution, Industry 4.0 following the development of many new industrial automation technologies in the manufacturing sector. Among the most important factors is the intelligent digitization of efficient manufacturing systems with four main drivers: Internet of Things, Industrial Internet of

Things (IIoT), smart manufacturing and cloud manufacturing [31]. It is important to emphasize that the revolution 4.0 allows manufacturing plants to be transformed into a fully integrated, mechanized and optimized production stream following the nine pillars of Industry 4.0 [32]. Industrial automation, cited as the most important pillar, uses flexible control systems to perform complex tasks autonomously, efficiently and accurately in production lines [33] through systemic self-learning.

Industry 4.0 has enabled the integration of new equipment, knowledge, concepts [34], standards, interconnected-ness, technical assistance, information transparency and decentralized decision-making [35] within an organization. The main challenges faced by manufacturing companies include organizational flexibility and agility to keep up with dynamic market trends [36], timely adaption to technological innovations and increased technological efficiency [37]. As a result, industries that aim to stay up-to-date with the latest developments needs to be more inclusive and agile in responding to industry changes and adopting new technologies as per industry requirements. Recent trends in manufacturing include mass customization, personalized products and comprehensive product designs [38], which required advanced equipment and technology. However, the customer is the most important link in any manufacturing system, as they ultimately decide what he buys and from whom.

Individual industries need to look for new resources, quality leadership that has the ability to deal with new developments and bring needed changes to the company and diversify the knowledge portfolio of its employees. These factors will certainly help in dealing with the Industry 4.0 revolution. Large companies and corporations will certainly have an advantage from this revolution and will move towards sustainable manufacturing practices [17].

In manufacturing companies, the management process relates not only to the worker, but also to other elements of the production system. This indicates the need for professionalism and practical skills of an interdisciplinary attempt to analyze the production process. Decision-making is an integral part of modern management. Decisions are made to sustain the activities of all economic activities and the functioning of the organization with the help of the sources it has [39]. Implementation of Industry 4.0 solutions would certainly improve and speed up the process of making such decisions.

Many companies are enthusiastic about introducing new technologies into production processes, especially those related to Industry 4.0. Thus, there has been a need to evaluate various existing techniques, tools and methods from the point of view of their suitability for Industry 4.0. Unfortunately, the introduction of modern technologies into industrial life requires companies to redesign their management systems [40]. What's worse, despite promising predictions, they do not always succeed or the effects of their introduction are quite different from those expected. Initial enthusiasm and success can turn into failure.

The implementation of Industry 4.0-related technologies not only requires significant financial investment, in return for which companies expect economic benefits, such as a strong positive impact on process efficiency, more efficient interaction between customers and suppliers, product improvements, significant reductions in energy demand or related emissions. For instance, metallurgical companies equipped with digital and smart technologies can lead to their evolution into smart companies over time, and their cooperation with other companies in the chain will help create a smart value chain. Industry 4.0 poses a significant challenge for Polish companies in this industry. According to Gajdzik [41], scientific research and statistical data confirm that intensified efforts to develop the Industry 4.0 concept are already being made in steel mills. She also highlights that in the Polish steel industry, it can be seen that there are al-ready companies implementing the Industry 4.0 concept and taking concrete actions towards its adoption.

Kellner and co-authors [42] pointed out that during the conception of Industry 4.0, monitoring and regulation technologies for production in automotive and aviation were already at a high level. Therefore, in terms of readiness to adopt the new elements of Industry 4.0, companies in auto-motive and aviation are much better prepared than companies in the metal industry.

The implementation of Industry 4.0 currently mainly concerns large companies. However, the economy of most European countries is based on the activities of small and medium-sized enterprises (SMEs), and which are responsible for the bulk of GDP in each country. For this reason, the further development of the Industry 4.0 concept depends on adapting its assumptions and solutions to the needs of SMEs [43].

Industry 4.0 presents a significant challenge for businesses in general, but it is particularly problematic for small and medium-sized enterprises (SMEs). Unfortunately, the readiness of SMEs to implement the objectives of Industry 4.0 through new concepts, as well as their ability to meet this challenge, are unfortunately very limited. The smaller the SMEs is , the greater the risk that they will not be able to take advantage of this industrial revolution is [44]. The introduction of Industry 4.0 is often associated with difficulties, especially significant financial expenses, which, according to many researchers, means that most manufacturing SMEs are currently not yet ready to implement the Industry 4.0 concept [45, 46].

The authors [47] discovered that for most SME companies, the digital revolution presents significant problems and cannot be implemented in the theoretical way indicated in the literature. They emphasize that, in addition to large financial outlays, it creates difficulties from a strategic difficulties. Other researchers [46, 48] identified a set of barriers and obstacles that SMEs face when implementing Industry 4.0 and classified them into six categories: financial/economic, cultural, competence/resources, technical, legal and implementation process. On the other hand, Mamad [49], following other authors such as [50], identified several challenges and problems related to the

implementation of Industry 4.0, with some of the most important being:

- uncertainty about financial benefits due to lack of demonstrated business cases to justify investments,
- lack of strategy to coordinate activities across business units,
- lack of talent and capacity, such as data scientists,
- lack of courage to make a radical transformation,
- cybersecurity concerns with third-party vendors.

Thus, it is important to keep in mind that the introduction of new technologies and practices in SME enterprises, especially those related to Industry 4.0, is always fraught with risk [51] and presents significant challenges for them. As evidence, the survey of manufacturing SME companies in West Virginia, USA, in 2017 confirmed the difficulties faced by SMEs in implementing intelligent manufacturing [52].

The implementation of changes within the framework of Industry 4.0 is crucial for sustainable development as it integrates ecological, social, and economic aspects. On the one hand, modern technologies enable more efficient resource and energy use, contributing to environmental protection. On the other hand, they support the creation of new, more efficient production models that foster economic growth. Furthermore, Industry 4.0 facilitates the development of new skills and job opportunities, improving the quality of life for workers, and promoting social inclusion through more di-verse and flexible employment models that consider the needs of local communities. Many researchers have pointed out this significant impact.

The environmental dimension focuses on the trend-aligned use and renewal of natural resources, aiming to minimize the use of toxic substances, raw materials, and energy. These objectives can be achieved through recycling, resource re-generation, designing processes and products that reduce consumption, replacing non-renewable resources with renewable ones, and implementing a circular economy model. Industry 4.0 technologies, such as energy consumption monitoring, enhance energy efficiency and reduce CO_2 emissions, thereby improving business performance. These transformations create opportunities for sustainable production, enabling the creation of closed value loops, resource and tool reuse, as well as machinery modernization, resulting in waste reduction, limited physical transportation, and decreased emission [53, 54, 55, 56, 57].

In the social dimension, an organization should strive to create a safe working environment, focusing on collective learning and the development of employee competencies. Industry 4.0 brings numerous benefits to employees, including higher job satisfaction and better compensation, particularly in research and development departments. The introduction of new technologies will lead to changes in employee roles within manufacturing companies, but it will require proper training. Employees will need to acquire personal, social, operational, and technical skills, such as knowledge of networking technologies, data analysis, and information processing. These changes may result in a reduction in the number of jobs in the industrial sector and an increase in the replacement of labor by capital, leading to social costs. At the same time, the nature of work will shift, becoming more technology-oriented. However, empirical evidence on this topic remains limited [53, 57, 58, 59].

In the economic dimension, the goal is to achieve positive financial results for the organization, and the implementation of Industry 4.0 technologies brings numerous benefits to companies. A key advantage is the use of cyber-physical systems (CPS), which enable the reduction of material costs by decreasing the number of defective products and optimizing production processes in real-time. Additionally, Industry 4.0 allows for reduced machine downtime and setup time through quicker problem detection. Early identification and elimination of defects lead to cost savings and increased production efficiency. The introduction of these technologies also improves work efficiency, for example, through human-robot collaboration. Another benefit is better inventory management, optimized demand forecasting, and reduced overproduction. Industry 4.0 technologies also enhance product and process quality by solving problems and correcting errors in real-time. Furthermore, advanced analytics for demand forecasting reduces waste, while shorter research and development times accelerate product market launches, thereby increasing revenue. Innovative services also enable longer product lifecycles through repair and maintenance [53, 57, 60].

Digital technologies of Industry 4.0 can significantly support the achievement of sustainable development goals and the circular economy by companies. Therefore, a manufacturing company should initially determine which approach to sustainability it intends to adopt – whether it will be reactive or proactive – and set specific circularity goals it aims to achieve (e.g., defined environmental outcomes). By taking these steps, the company will be able to precisely identify the digital technologies in which it should invest to effectively achieve its set goals and drive changes towards sustainable development [61]

Industry 4.0, along with the digital technologies and principles that define it, enables companies not only to improve cross-functional collaboration but also to achieve better integration with both internal and external stakeholders. Through the use of advanced tools such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics, organizations can effectively manage information, fostering smooth data exchange and better coordination of activities at all levels. Industry 4.0 also contributes to strengthening the knowledge base and developing advanced production competencies that are essential for implementing technological innovations and sustainable development. It also promotes organizational capabilities that are crucial for introducing sustainable innovations, such as the so-called "green absorptive capacity" (the ability of organizations to absorb and adapt ecological technologies), sustainable partnerships, and a focus on innovations that support the development of responsible, eco-friendly solutions [62].

Thanks to these features, Industry 4.0 significantly enhances an organization's ability to introduce innovations in green manufacturing processes, as well as to effectively develop or reintroduce eco-friendly products that are competitive in the market. The technology enables businesses to implement more sustainable and cost-effective solutions, contributing to a reduction in their environmental impact. Moreover, integration with value networks and partnerships within Industry 4.0 promotes a more sustainable approach to innovation, allowing organizations not only to develop products but also to consider their impact on society and the environment, which is crucial for long-term competitiveness and corporate social responsibility.

Shabur [63] claimed by modern technology, is expected to be beneficial for the environment. In the era of Industry 4.0, the integration of communication and information technologies has created a strong link between industrial production and modern technologies, resulting in increased scalability, competitiveness, and effective knowledge acquisition. Industry 4.0 encompasses a set of principles, recommendations, and technical innovations that support the development and efficient operation of both new and existing industrial plants. This model allows customers to choose from various production models, utilizing flexible robotics, advanced information systems, and communication technologies that can be adapted to different production levels, thereby enhancing the efficiency and flexibility of processes.

It is important to note that the implementation of Industry 4.0 principles and the integration of sustainable development goals may encounter several barriers that could hinder the successful achievement of these objectives. First and fore-most, the adoption of new technologies involves high initial costs, both in terms of purchasing advanced equipment and integrating digital solutions with existing production systems. For many companies, particularly those with limited re-sources, these investments can pose a significant challenge. Furthermore, the process of implementing advanced technologies requires substantial investments in employee training and infrastructure modernization, which could slow the pace of plan execution.

In the context of sustainable development, another challenge may be defining clear and measurable environmental goals, which complicates the monitoring of progress and evaluation of the effectiveness of actions. Companies may face difficulties integrating ecological solutions with existing production models, especially when changes require significant modifications to processes and organizational structures. Additionally, the introduction of new technologies may meet resistance from employees, who may fear job losses, changes in their roles within the company, or the need to adapt to new tools. External stakeholders, such as suppliers or customers, may also have concerns about the costs and availability of new solutions, introducing additional uncertainty into the transformation process.

METHODOLOGY OF RESEARCH

The research results presented in this paper are a continuation of the previous authors' paper [64]. The main aim of this paper was to analyze the level of automation and robotization and to assess the current state of enterprises from the SME sector and to determine their interest in using modern communication channels based on the platform structure enabling optimization of the product portfolio of producers based on consolidation and optimization of the investment strategy in terms of obtaining modern flexible technologies compliant with the 4.0 standard. In the article the results of research related to the impact of the changes of the industrial revolution 4.0 on small and medium-sized enterprises in the Czestochowa Industrial District were presented. The research revealed that 63% of the research companies ex-pressed an interest in participating in a platform that brings together similar companies with similar problems, while another 16% were also interested in, but not certain. 63% of respondents were interested in the shared purchase and use of machines, another 24% are not quite sure. According to respondents, co-employing workers was a good idea, with 72% responding yes and 13% responding rather yes. This would help solve employment problems, especially regarding the hiring of specialists, who are in short supply in the market all the time. Companies are also interested in exchanging various information about machines and employees. An important point is the possibility of selling/purchasing production capacity, which 74% of the surveyed companies declared, and 23% not quite sure.

The authors indicated the need for continued the research, which has focused on similar evaluation, but in other industries, such as mining [65], and furniture [66]. One path of researches involved evaluating a platform that had been created by SME metal industry companies in the Częstochowa region. In this paper, the authors decided to present the effects of the platform's functioning in the form of a case study.

The technology knowledge-sharing platform described in this paper is a tool that enables the sharing and exchanging information and experience between different entities from metal sector. In terms of the 4.0 transformation process, the platform was expected to bring many benefits, including:

- Facilitate access to up-to-date technological information and the latest solutions – the platform allows for easier access to the latest information and solutions, which enables for faster and more effective implementation of innovations.
- Fostering sectoral cooperation – the platform allows cooperation between different entities, allowing for better utilization of each entity's potential and experience.
- Increasing R&D efficiency – the platform allows for the exchange of information and experience between different entities, which results in for better planning and coordination of research and development.
- Supporting the development of competencies – the plat-form enables for the sharing and exchange of

knowledge and experience between different entities, which facilitates the development of competencies and skills that are key to the 4.0 transformation.
- Support for market development – the platform allows for collaboration between different entities, leading to market development and the creation of new business opportunities, as evidenced in the case study described in the paper.

An important identified barrier to the operation of such a platform from the point of view of SMEs is the fear of disseminating their own knowledge and experience and losing their position in the market. Pilot research have shown that many SMEs may be concerned that their knowledge and experience will be exploited by competitors or their market position will be compromised. Platforms employ various types of protection mechanisms [22, 67, 68, 69, 70]:
- Platforms can offer different levels of access to knowledge and expertise and security features such as encryption and authorization to ensure that only authorized parties can access information.
- Use of licenses – Platforms can offer licenses that allow knowledge and expertise to be used only for a specific purpose and scope, thus protecting the interests of in-formation owners.
- Use of NDA (non-disclosure agreements) – Platforms can require their users to sign a confidentiality agreement that obliges them not to share information obtained from the platform with third parties.
- Use of a partnership-based model – Platforms can encourage collaboration by establishing partnerships that allow information and experiences to be shared without fear of competition.
- Creating virtual consortia – Platforms can create virtual consortia in which participants can share information and experiences, with privacy and security.

In the case of the platform described in the paper, one deals with three entities which used the platform to exchange knowledge and experience and also to consolidate capital in the 4.0 transformation process on the basis of an open partnership model and a real (not virtual consortium of three SME metal industry entities). In addition to the positive aspects of this approach, we can include:
- Increasing the efficiency of operations by leveraging the knowledge and experience of individual partners.
- Ability to share risks and costs of ventures.
- Strengthening market position through networking and mutual support.
- Increasing innovation by bringing together diverse perspectives and viewpoints.

Difficulties and drawbacks of this approach were also revealed in the form of:
- Difficulties in coordinating the activities and goals of individual partners, which can lead to delays and project failures.
- Conflicts of interest between partners, which can lead to broken cooperation.
- Difficulties in managing different levels of commitment and contribution from individual partners.
- Problems related to sharing information and know-how, as partners may fear of protecting their interests.
- Difficulties in determining and accounting for profit and cost sharing.

Despite attempts to counter and minimize the problems by changing management and communication styles and defining long-term commitments, the resulting consortium faced the problem of insufficient availability of production capacity and the inability to expand at the current location, which did not anticipate as much development.

To present and evaluate the platform's performance, the authors used so-called mixed-methods research. This is a research approach in which researchers collect and analyze both quantitative and qualitative data within the same study.

The authors analyzed two groups of data, i.e. qualitatively from two data sources (case studies and literature studies) and quantitatively, which made it possible to identify basic measures of company performance in terms of the production process.

Regarding the limitations associated with mixed-methods research, they as follows [71, 72]:
- It is more difficult to coordinate and analyze data from different sources, which can lead to interpretive difficulties.
- Some research methods may be inappropriate for a particular research topic.
- For some research projects, data from different sources may be incompatible or difficult to compare.

Advantages include [71, 72]:
- It provides a more comprehensive and nuanced under-standing of the phenomenon or problem, as they allow the use of different perspectives and research methods.
- The use of both quantitative and qualitative methods enables the collection of diverse data, which increases the reliability of the study's results.
- The ability to integrate and compare results from different research methods allows researchers to confirm or challenge their hypotheses.
- Mixed-methods study allows for better interpretation and synthesis of data from different sources.

Wachnik [73] following Czakon [74] wrote that in management science and quality research, various types of problems, especially those related to lack of knowledge or uncertainty, should be addressed using existing research methods. One method that is used in such situation is the case study. Such research should contain a detailed description of a usually real-life economic phenomenon, such as an organization, a management process, its elements or the organization's environment, in order to formulate conclusions about the causes and consequences of its course.

The case study presented in the article is of a descriptive-evaluative and longitudinal nature:
- Descriptive: Case studies can be descriptive in nature, providing a detailed account of a particular event, organization, or phenomenon. Descriptive case studies seek to understand the current state of a particular

topic and provide a snapshot of the situation being studied.
- Evaluative: Case studies can be evaluative in nature, seeking to evaluate the effectiveness of a particular pro-gram, policy, or intervention. Evaluative case studies focus on assessing the impact of a particular intervention and determining whether it was successful or not.
- Longitudinal: Case studies can be longitudinal in nature, following a particular case over an extended period of time. Longitudinal case studies seek to understand how organizations or phenomena change over time and how they adapt to changing circumstances.
- The results of the evaluative, descriptive, and longitudinal analysis of the case study can be used in several ways, including:
- Informing future decision-making: The results of the case study analysis can be used to make future decisions about increasing production capacity. By identifying the successes and challenges facing the company, owners can make informed decisions about reorganizing operations or building a new facility.
- The analysis also allows for the verification of previous decisions and the determination of their effects.
- Identification of best practices: The case study analysis can identify best practices in implementing and scaling Industry 4.0 technologies.
- By analyzing the factors that contributed to the success of the merger and the challenges it faced, the case study can help identify key success factors and potential barriers to the adoption of Industry 4.0.
- Efficiency: the analysis of a case study can be used to compare the efficiency of other companies in the manufacturing industry. By comparing the experiences of this company with other companies in the industry, stakeholders can identify areas that need improvement and opportunities for development.
- Better understanding of Industry 4.0: Case study analysis can contribute to the development of theories related to the adoption and scaling of Industry 4.0 technologies in the manufacturing industry. By presenting a real-life example of challenges and opportunities related to the adoption of Industry 4.0, a case study can help in future research and theory-building in this field.
- The results of the evaluative, descriptive, and longitudinal analysis of the case study can be used in several ways, including making decisions in the future, identifying best practices, comparing performance, and better understanding Industry 4.0. Through a detailed description of this company's experiences, the case study analysis can help acquire information about future research and practices in the manufacturing industry (metalworking).

The research utilized both qualitative and quantitative data from 2018-2022 which was obtained from the three SME metal companies that participated in the previous research. Additionally, data from a newly established entity (the jointly created platform) from the years 2019-2022 was also used. The research began by characterizing the research entities and analyzing the state of affairs in 2018, before the decision to create the platform, based on previous surveys and data provided by the companies. A face-to-face inter-view session was then conducted to describe the jointly created platform and analyze the data provided by the companies. This analysis not only provided insight into the activities of the research facilities before and after the creation of the platform, but also provided information about the effects of the platform. Furthermore, the authors reviewed literature related to similar platforms in the market.

The evaluation of the functioning of individual stakeholders and the created facility was based on Key Performance Indicators (KPI). KPIs are defined as a set of measures focusing on critical aspects of organizational performance that are crucial for the current and future success of the organization, according to David [75]. Many indicators are not publicly disclosed by companies due to industrial secrecy, such as financial indicators.

Small companies usually use simple performance indicators (such as the number of units produced per unit of time) and quality indicators (such as the number of production defects) to reflect production. In the case of building modern Industry 4.0-based facilities, the software of purchased machinery and equipment enables monitoring of most of the defined KPIs. However, in the examined facilities, they were not used to monitor and improve processes. They were limited to the generally known and acceptable overall efficiency of machines and equipment. The study selected those related to production and possible to calculate for individual stakeholders, as well as those to which these stakeholders agreed, namely quality rate, availability rate, and efficiency rate.

The case study was conducted based on data obtained from the research facilities and archival materials that were not publicly available, as well as analyzed records from direct interviews with individual stakeholders.

The utilization of machines and equipment with approximate overall efficiency values and based on selected KPIs was analyzed. The analysis took into account the volume of production, the time of machine and equipment utilization, the number of complaints and returns, and indicators of human work efficiency. The lack of full monitoring of KPIs by individual stakeholders was observed, with only monthly reports being provided. Therefore, the data may be subject to methodological error, and the results obtained should be considered as estimates.

The descriptive analysis of the case study over a long period of time confirms the validity of the decisions made. Thanks to the study, it was possible to verify the operational and strategic decisions of individual stakeholders as well as the entire consortium, and to develop recommendations for consolidating facilities in accordance with Industry 4.0.

The next analysis focused on the barriers encountered during the implementation of Industry 4.0 by the studied enterprises during their collaboration, as well as an analysis of the risks that became apparent during the

operation of the consortium created by these entities. The methodology for identifying the risks and barriers associated with Industry 4.0 implementation involved a multi-stage approach focused on collecting qualitative insights from key stakeholders. This process included in-depth interviews and consultations with employees and managers within the companies involved, allowing for a nuanced understanding of their operational challenges and strategic limitations. By examining the experiences of the consortium's participants over a three-year period, researchers were able to capture both the initial and evolving barriers, including financial constraints, technological adaptation issues, and capacity limitations. This longitudinal analysis provided a comprehensive view of the risks at different implementation stages, enabling the development of targeted strategies to address each barrier effectively.

The authors emphasize that only a small amount of data was revealed in the article due to the confidentiality of the activities of both individual stakeholders and the consortium.

RESULTS OF RESEARCH

Characteristics of the research objects

The research presented a brief overview of the research facilities for 2018, before the decision was made by the entities to establish a new production entity on a consortium basis.

Object A:

Object A is a manufacturer of fasteners such as bolts, nuts, washers, etc. All products are made of high-quality steel and are designed for use in the engineering industry. The company has 24 employees. It is an enterprise characterized by the type of small and multi-serial production. Work is carried out in a single-shift system.

The values of the basic coefficients were estimated based on the company's records. The enterprise did not monitor the KPIs. These indicators were as follows:

- Utilization rate of the machines: OEE 50-60%.
- Quality indicator: 80-85%.
- Availability rate: 60-65%.
- Efficiency rate: 60-65%.
- On-time orders rate: 70-75%.
- Stock turnover rate: 4-5 times a year.
- Sales efficiency rate: about 80%.

The company during this period was characterized by a low level of automation of production, and planned improvement activities were lacking.

Object B:

Facility B is a manufacturer of small-gauge steel components, axle products for the automotive industry. It employs 32 workers. As in the previous case, this is an enterprise characterized by a type of small- and multi-serial production. However, in this case, the work is carried out in a two-shift system (single shift, with the possibility of activating a second shift in case of increased order volume).

KPIs were monitored by the company and were as follows:

- Utilization rate of the machines: 70%.
- Quality indicator: 85%.
- Availability rate: 75%.
- Efficiency rate: 71%.
- On-time orders rate: 85%.
- Stock turnover rate: 9 times a year.
- Sales efficiency rate: about 90%.

It should be added that this enterprise has an average level of production automation, and has implemented basic lean improvement tools.

Object C:

Object C is a manufacturer of machine components such as shafts, gears, bushings, etc. These components are made from various types of metals, such as steel, aluminum, copper, etc. The company employs 20 workers. All products are customized according to individual customer needs. There-fore, it is an enterprise characterized by the type of unit and small-serial production. Work is carried out in a single-shift system.

The values of the basic coefficients were estimated based on the company's records. The enterprise did not monitor the KPIs. These indicators were as follows:

- Utilization rate of the machines: 55-65%.
- Quality indicator: around 88%.
- Availability rate: 65-75%.
- Efficiency rate: 65-75%.
- On-time orders rate: 60-65%.
- Stock turnover rate: 4 times a year.
- Sales efficiency rate: about 90%.

This enterprise has an average level of production automation, and has implemented basic lean improvement tools.

Barriers to the Implementation of Industry 4.0

The analysis of the activities of the examined entities in 2018 was supplemented with an analysis of the barriers that these enterprises may encounter when implementing solutions within Industry 4.0. These barriers were identified through interviews with employees of the studied entities, especially top management. These risks can be mitigated to some extent through appropriate actions taken by these entities. The following barriers were identified:

- Financial Barriers: By pooling resources, companies can distribute the costs of investing in Industry 4.0 infrastructure and technologies. Company C, with a larger budget, can invest in technology upgrades, while Companies A and B contribute to operating costs and share resources as they are used. In this way, all three companies gain access to shared tools and equipment, minimizing the individual costs of purchasing and maintaining modern solutions.
- Shortage of Digital Skills: Company A, which has a trained team of IT specialists, can take the lead in data analysis and Industry 4.0 system implementation for all three companies. This allows the other companies to benefit from the know-how and experience of experts without the need to hire additional personnel. As part of the collaboration, Company A organizes training sessions for the teams of Companies B and C to enhance their digital competencies.

- Technological and Infrastructure Limitations: Company B, which has a modern production line, can make it available to partners for testing new solutions and equipment. This enables Company C, which is planning investments in infrastructure, to gain insight into the operation of the latest automation systems and plan the implementation of appropriate technologies. Company B, utilizing resources from Companies A and C, also upgrades some of its IT equipment to facilitate process integration among the companies.
- Lack of Strategy and Awareness: Through a joint project, the companies can develop a plan for implementing Industry 4.0, based on an analysis of each partner's capabilities and limitations. Company A, with experience in analytics, can lead efficiency analyses of implemented solutions, which will help in setting appropriate strategies for the future. With a shared strategy, each company can make more informed and coordinated decisions, reducing the risk of inefficient resource utilization.
- Interoperability and Standardization Issues: The companies decide to adopt common technological and operational standards to facilitate the integration of systems and devices. Company A, as the IT leader, selects compatible solutions based on open protocols that are easy to integrate. Companies B and C adjust their systems to these standards, ensuring seamless data exchange and enabling mutual cooperation of devices and systems on the production line.
- Cybersecurity Concerns: By pooling resources, the companies can jointly invest in network security and IT infrastructure monitoring. Company A, with its IT team, also conducts audits and implements data protection systems, minimizing the risk of cyberattacks. This approach allows all three companies to benefit from advanced cybersecurity solutions that would be challenging to implement individually.
- Limited Scalability of Collaborative Initiatives: The companies establish a project management structure to coordinate joint actions and decision-making. A council is formed, consisting of representatives from each company, to set priorities and timelines for technology implementation and monitor the scalability of solutions. By sharing responsibilities and schedules, the companies can support processes in an efficient way that maintains flexibility for all participants.
- Lack of Boldness for Radical Change: Through mutual engagement and support, each company feels more confident in making bold transformational decisions. Shared successes and the exchange of experiences add motivation for further implementations and overcoming barriers related to Industry 4.0. Mutual support reduces the fear of change, and the established collaboration al-lows all participants to benefit from joint actions.

By pooling resources, the three SMEs are able to effectively overcome most of the barriers to implementing Industry 4.0. Collaboration allows them to reduce costs, increase access to advanced technologies, address skill gaps, and improve the interoperability and security of their systems. The integration of resources contributes to creating a scalable collaboration model that enhances the operational efficiency of each company and supports their long-term development within the digital transformation. Additionally, considering the stages of change related to the implementation of Industry 4.0, other types of risks can be identified, such as:

1. Milestone: Planning and Preparation Stage:

- Lack of a Precise Plan and Strategy: Without a detailed implementation plan and a cohesive strategy, scheduling issues may arise, leading to inefficient resource management and delays. Each company should clearly define its objectives, budget, and resources needed to complete the project. Introducing control schedules and clearly assigning responsibilities to each company could help reduce the risk of unforeseen delays and ensure a smooth project flow.
- Differences in Company Goals and Priorities: Each company may have different objectives regarding Industry 4.0 implementation, which could lead to conflicts of interest and difficulties in reaching consensus. For ex-ample, one company may focus more on cost reduction, while another prioritizes process optimization. Organizing consultative meetings and workshops can help align expectations and establish shared values that will guide project execution.
- Limited Availability of Financial Resources: Industry 4.0 involves high investment costs, which not every company may be able to fully cover. It is worth considering external funding sources, such as EU grants or loans on favorable terms. Companies can also develop a phased spending plan to reduce financial strain and better align costs with their budgets.
- Risk of Insufficient Technological Awareness: A lack of understanding of Industry 4.0 technologies by decision-makers could lead to poor decisions, selecting inappropriate technologies, or adopting suboptimal solutions for the project. Conducting educational sessions and consulting with experts can help decision-makers gain better insight into the technological aspects of Industry 4.0 and how they align with business needs.

2. Milestone: Implementation Stage:

- System Interoperability Issues: Integrating technologies from different companies may encounter technical difficulties due to system and communication protocol in-compatibilities. One solution is to adopt a uniform communication standard or use a technology integrator to create the necessary interfaces. Interoperability issues can delay implementation and increase costs, so it’s crucial to plan this stage well in advance.
- Lack of Skills and Human Resources: Employees may lack the necessary skills to operate integrated technologies, leading to errors, downtime, and reduced operational efficiency. Companies can jointly invest in training and skill development programs for teams to enhance their readiness for the new systems.

Additionally, outsourcing some operations at an early stage could help reduce the risk of errors.

- Risk of Unexpected Costs: During implementation, additional expenses may arise, such as infrastructure upgrades, extra training, or the need for additional equipment. Companies should establish a reserve fund to cover unforeseen expenses. Regular budget monitoring and cost analysis will enable a faster response to potential financial issues.
- Difficulties in Synchronizing Operational Processes: Different work models and operational procedures across companies may cause synchronization issues, affecting project efficiency. Implementing standardized operational procedures and conducting best practice workshops could help improve communication and co-ordination among the companies, reducing the risk of operational conflicts.

3. Milestone: Testing and Calibration Stage:

- Lack of Consistent Quality and Safety Standards: If different standards for quality and safety interpretation are applied, discrepancies in the level of protection and product quality may arise. The companies should develop common quality and safety standards that com-ply with industry and legal requirements. Audits and final testing can help identify differences and allow for corrections.
- Risk of Incomplete Optimization: Testing may reveal that the system does not fully meet the specific needs of each company, which may require additional changes that could affect the project's timeline and budget. To minimize this risk, companies should involve process optimization specialists and conduct test simulations be-fore the system's final launch. This practice will help detect potential issues early.
- Risk of Non-compliance with Legal Regulations: New technologies must meet specific legal requirements, such as data protection laws or product quality certifications.

Implementing Industry 4.0 solutions by small and medium-sized enterprises (SMEs) is a critical process for their survival and competitiveness in an increasingly digitalized market. Identifying and analyzing potential risks and barriers at various stages of implementation – from planning and implementation to testing – is essential because it helps companies better prepare for challenges and optimize their implementation processes. In the face of diverse resources, priorities, and financial capabilities of SMEs, a clear strategy and risk management are crucial to minimize potential failures and improve the effectiveness of the changes being made.

Thanks to such analyses, companies can better handle difficulties such as lack of financial resources, technological limitations, or differences in partners' priorities. A thoughtful approach to harmonizing actions and standardizing procedures not only improves communication and coordination between teams but also better aligns with industry standards for quality and safety. Successfully implementing Industry 4.0 solutions can not only increase productivity and service quality but also open up new opportunities for development and collaboration, strengthening the companies' position in the market.

Description and evaluation of the performance of the platform (consortium)

The presented business entities had to make a choice regarding their further development model, taking into account their organizational structure, type and form of production, human potential, and technological equipment. A preliminary qualitative assessment revealed that the research entities were not well-equipped and lacked the financial re-sources to undergo digital transformation, which is a com-mon characteristic of SMEs. This finding was also supported by previous studies conducted by the authors [42] as well as literature studies [76, 77, 78].

In the presented case stage, the impetus for further development was not solely based on knowledge transfer based on the described platform. An expert interview conducted with the management of the entities in 2022 revealed several factors that influenced the decision to establish a new economic entity for development. The period of the strategic decision in 2018 was identified as one of the factors by the executives:

- shortage of skilled labor with the competencies required by Industry 4.0,
- the need to move to personalized production,
- increased demand for more personalized product,
- the need to improve productivity, quality and reliability of supply,
- the barrier to small and medium-sized companies obtaining adequate funding for the transformation,
- the need to integrate vertically and horizontally in every sphere of business to improve efficiency,
- high costs of implementation of the new solutions,
- the need to establish an optimum (balance point) between implementation costs and real benefits and profit,
- insufficient equipping of entities for individual transformation efforts,
- lack of support for small entities (SME sector) in the transformation process, and lack of defined transformation strategies focusing on the SME sector.

The main factor that determined the choice of a development model based on a new economic entity was the ability to raise funds through generating new jobs and implementing innovative process solutions, achieving economic scale by pooling resources and competencies, easier access to new technologies and Industry 4.0 solutions, improving operational efficiency by optimizing processes and reducing costs, and increasing investment opportunities through pooling of financial resources. Mutual trust resulting from previous cooperation in mutual subcontracting of orders was identified as another important factor, along with the work system in which all facilities worked in single shifts, except facility B which could run an extra shift, allowing for a three-shift work system and division of the platform's working time into three parts. The costs associated with implementing modern solutions

were distributed among all participants of the platform, which was also noteworthy.

Based on the presented data, it can be assumed that the platform created by the research facilities has fulfilled its purpose to some extent through the combination of entities and optimizations, or the choice of a new development model. At the same time, the subjects did not choose the recommended model of creating an all-encompassing intelligent production system that guarantees a more productive and flexible nature in terms of all available production time. But they chose a rigid, equal-for-all allocation of available production time to infrastructure, which was a flawed assumption from the outset and did not guarantee optimal use of existing potential. The turning point in the approach to utilizing the potential and breaking with the inefficient allocation of available time was the beginning of 2020 and the occurring labor shortage related to the COVID-19 pandemic. As a result, it was possible to optimize the product family and take advantage of the possibility of a digital hall, which directly affects productivity, as well as the quality of processes. This turned out to be possible through holistic map-ping of the target value chain.

The presented example shows that the adoption of this development strategy has enabled the new entity to access Industry 4.0 technology at a lower investment cost com-pared to a unitary implementation by a single company. This approach unleashed additional production potential by achieving a so-called higher level of agility (flexibility) by responding quickly to changes that cannot be predicted in practice. Breaking the misallocation of infrastructure access time has enabled so-called system configurability and adaptation of production and also functional capabilities to changing orders.

The Lean instruments used by facility D, such as mapping, standardization of work methods, SMED, elimination of bottlenecks, and application of 5S, are all commonly used tools in Lean manufacturing. The use of these tools aims to improve operational efficiency, reduce waste, and increase productivity. In this case, the shortage of specialized employees likely created a need for the facility to optimize its processes and utilize Lean tools to make up for the labor shortage. The application of Lean tools also suggests that the facility may have identified inefficiencies in its processes that could be addressed through process improvement initiatives.

The reorganization that occurred due to shortages in the availability of specialized employees forced the D facility to seek out external sources of knowledge and help regarding Lean instruments and solutions. Company D has recognized the importance of obtaining lean knowledge to improve their operations and has decided to cooperate with the Association of Quality and Production Managers. This association has extensive experience in the implementation of lean solutions in the ceramics and metal industries, which makes them a valuable partner for company D in their quest for lean knowledge. Value Stream Mapping (VSM):

- Standard Work,
- Single-Minute Exchange of Dies (SMED),
- 5S,
- Elimination of Bottlenecks.

The implementation of these solutions required commitment and cooperation from all levels of the organization, as well as a willingness to continuously improve and adapt to changing circumstances. Due to the knowledge and support provided by the Association Quality and Production Managers Association, significant improvements were achieved in just 8 months.

After eliminating the inefficient distribution of availability time to the infrastructure of individual facilities and the execution of their non-optimized order portfolio, an OEE of 95% was achieved This is due to the improvements in avail-ability, performance and quality that Industry 4.0 systems can provide, such as:

- advanced monitoring and control systems that can detect and correct problems in real time, reducing downtime and maximizing equipment availability,
- optimization of machine speeds and cycle times that can increase production efficiency and productivity,
- advanced data analysis and machine learning that can detect and correct defects in real time, improving quality and reducing the need for rework,
- tracking and data collection that can optimize the production process and improve OEE.

Upon commencing operations, Facility D employed an 8-hour equipment availability change management system for each stakeholder, with employees assigned to each stake-holder separately for 5 days a week, 8 hours per day, with the option of overtime on Saturdays for large or urgent orders. Shifts were rotated weekly and production schedules were managed independently without transferring production to the next shift. Breakdowns were resolved by all stakeholders together or outsourced to external companies.

Due to the COVID-19 pandemic and prevailing market conditions, Facility D underwent a reorganization that included a reduction in employment. The lack of available employees due to extended sick leaves and holidays caused difficulty in fulfilling orders, resulting in the use of subcontractors. Additionally, some employees who had reached retirement age also left their jobs, which further reduced the number of available workers. The reorganization was necessary not only due to the product families produced by individual stakeholders but also for the optimization of machinery and equipment usage. The decision to reorganize was made jointly by the entire consortium.

The initial operation of Facility D utilized a system of 20 people per shift, which was later reconfigured to a total of 35 people. During the COVID-19 pandemic, 11 employees left their jobs, and an additional 4 employees left due to retirement age. The reconfiguration resulted in a reduction of employees, taking into account their competences.

In Figure 1, a model of enterprise development that takes into account the various stages of transformation was presented.

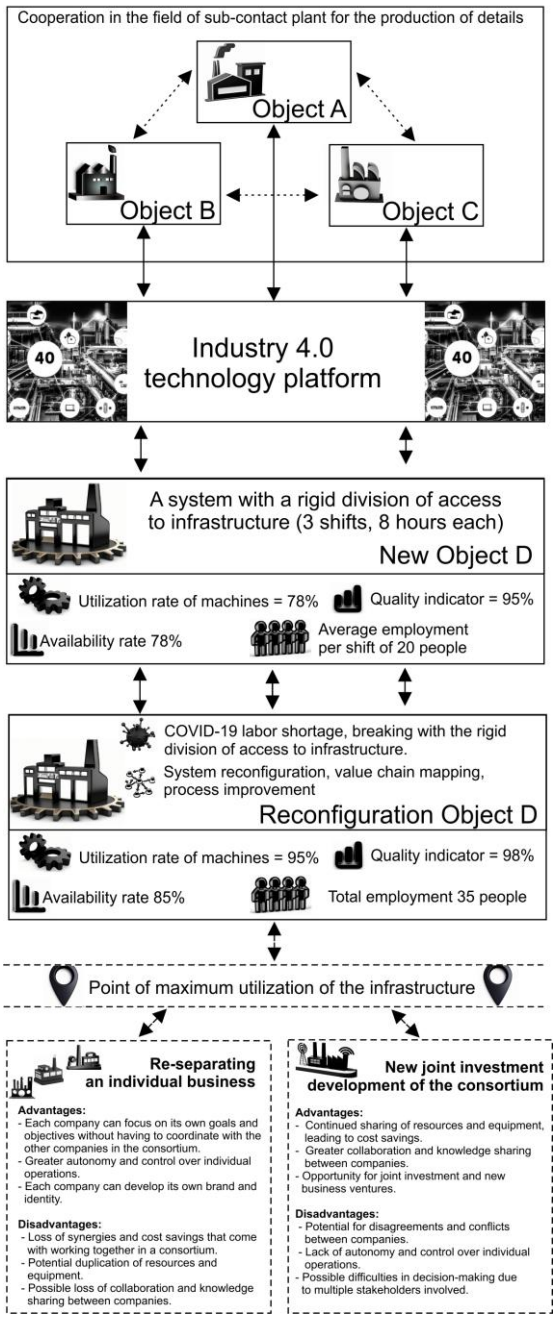

Fig. 1 A model of SME companies development in the aspect of Industry 4.0 Transformation

The high quality indicator and almost 100% quality control has significantly reduced logistics, warranty and returns liability costs. This has made it possible to lower prices for many products, resulting in a positive impact on order volumes. However, the production facilities are currently at a standstill because they lack the capacity to fulfill new orders and acquire new customers, leading to tension and conflicts between stakeholders who rely on the existing infrastructure. Spatial limitations prevent further equipment development at the current location. Increasing production capacity is no longer possible either by adding new equipment (there is no space for new equipment), hiring additional personnel (currently a three-shift work system) or implementing more efficient production processes. As a temporary solution, order prioritization based on factors such as delivery date, order size, and customer importance has been used, along with outsourcing production. However, this approach negatively impacts production costs, lead time, and quality control, leading to decreased customer satisfaction and potential loss of customers. Additionally, logistical problems arise, making it difficult to respond to changes in the market and customer needs.

The decision to divide a company or continue working together as a consortium can have a significant impact on the future of the organization. Both options have their advantages and disadvantages that should be carefully analyzed before making a decision.

Dividing the company and running businesses independently can provide each company with greater autonomy and control over its operations. This can allow for more focused and efficient operations as each company can tailor its activities to its specific needs and goals. However, there is a risk of losing the synergies and cost savings that come with working together as a consortium. There may also be a duplication of resources and equipment which can lead to in-creased costs.

On the other hand, continuing to work together as a consortium and investing in joint ventures can allow for continued sharing of resources and equipment, leading to cost savings. This can also provide an opportunity for greater collaboration and knowledge sharing between companies, which can result in improved efficiency and innovation. However, there is a risk of disagreements and conflicts between companies which can lead to difficulties in decision-making. Additionally, there may be a lack of autonomy and control over individual operations which can limit the ability of each company to achieve its specific goals.

After analyzing the pros and cons of the two proposed solutions for the consortium, it can be concluded that continuation of joint activity is a better solution for the future development of the company. By continuing joint activity, the consortium will benefit from the synergy effect, which will allow for the reduction of operating costs and better knowledge management. Additionally, risk minimization will be achieved by spreading risks across multiple stakeholders. The potential for innovation and growth is also greater in this scenario, as all stakeholders can bring their unique strengths and expertise to the table. Therefore, it is recommended that the consortium continue to operate jointly and invest in new opportunities to further their success.

The individual stakeholders aim to independently carry out new investments. However, the authors are of the opinion that simulation suggests that a better decision would be a joint investment in further development of the consortium.

Barriers to the performance of the platform (consortium)

The next analysis of the barriers to implementing Industry 4.0 focused on the period of the platform's operation over the following three years. This analysis, too, was based on discussions with employees of the studied facilities.

Additionally, actions that could counteract these barriers were identified. The following barriers were defined:

Year 1: Early Operational and Adaptive Risks:

- Staff Adaptation: Employees may need time to learn and adapt to the new, complex system. Insufficient training or lack of experience with integrated technologies can lead to mistakes, downtime, and production de-lays. At the initial stage, intensive training and continuous technical support are necessary to minimize potential issues arising from a lack of staff competencies.
- Initial Technical Issues: Any newly implemented system may encounter problems that were not detected during testing. These could range from minor malfunctions to more complex issues resulting from unforeseen integration difficulties. Such failures may lead to downtime and increased operational costs. Companies should have contingency plans in place to minimize downtime and access to technical support to quickly resolve emerging issues.
- Insufficient System Stability: At the start of operating an integrated system, there may be instability due to the ongoing adjustment of the system to the specific operational requirements of each company. These issues can lead to reduced production efficiency and limit the ability to fulfill orders.
- Additional Operational Costs: The initial phase of operation often requires increased financial outlays for maintenance, minor modifications, and additional training. If these costs were not accounted for in the budget, they could strain the companies' finances and cause tension.

Year 2: Issues Related to System Development and Adaptation:

- Low System Flexibility: Over time, it may become apparent that the integrated system cannot fully adapt to changing market needs, new customer requirements, or the introduction of non-standard products. In such cases, the lack of flexibility limits the companies' ability to adjust to market conditions and may lead to a loss of competitive advantage.
- Cybersecurity Risks: An integrated system, especially one that connects multiple companies, becomes more vulnerable to cybersecurity threats. The longer the system is in operation, the higher the risk of falling victim to hacker attacks, data breaches, or malware infections. Companies must regularly update security measures, conduct audits, and monitor the network to minimize threats.
- Rising Maintenance Costs: Systems require regular updates and servicing, which can become costly over time. Additional maintenance expenses may strain the budget, especially if companies have not set aside funds for such costs. As maintenance becomes more expensive, the profitability of the project may be undermined.
- Problems with Adapting to New Legal Regulations: Manufacturing industries must constantly adapt to new regulations, such as environmental protection, quality standards, or data protection. Implementing changes due to new legislation may require system adjustments, which can involve audits and updates.
- Potential Conflicts of Interest Between Companies: After a period of collaboration and system operation, differences in priorities between the companies may arise. Conflicts may occur regarding the allocation of re-sources, maintenance costs, or system modifications. To avoid escalation, companies should regularly set priori-ties and maintain transparent communication.

Year 3: Reaching the System's Maximum Load:

- Exceeding System Capacity: After three years of operation, the system may reach its maximum capacity and be unable to handle an increasing number of orders. This leads to downtime, delays in order fulfillment, and customer dissatisfaction, which affects the companies' reputations. If the system is not scalable, the companies will be forced to limit their operations or invest in new infrastructure.
- Technological Obsolescence: In the technology industry, hardware and software quickly become outdated. After three years of operation, the integrated system may no longer meet market standards, affecting the companies' efficiency and competitiveness. Updating or completely replacing the technology may be necessary, and the costs of these actions could be significant.
- Low Scalability: The system, originally designed for three companies, may fail to keep up with the growing needs of each. A lack of easy scalability may prevent the companies from further development, affecting their ability to handle a higher volume of orders and meet new customer demands.
- Decline in Quality and Performance: An overworked system may begin to operate less efficiently, leading to a decline in production quality and reduced performance. This can result in more complaints, increased production costs, and customer dissatisfaction, which could negatively impact financial results.
- Increased Tensions Over Resource Allocation: As the needs of each company grow, conflicts over resource al-location and priorities may increase. This can lead to tensions between the companies, especially if one re-quires more access to resources. Inability to manage such conflicts may result in weakened collaboration or the need to renegotiate the terms of system usage.
- Increased Risk of Infrastructure Failures: A system that is heavily exploited becomes more susceptible to failures. As it nears its performance limits, the risk of down-time and infrastructure failures increases, which can be costly and time-consuming to repair. Companies should consider implementing contingency plans and securing backup resources to maintain production continuity.

The analysis of operational and adaptive barriers during the exploitation of a platform within an industrial consortium reveals key challenges that can significantly impact

the effectiveness of Industry 4.0 implementation. At various stages of operation – from initial personnel and system adaptation, through development and adjustment to market requirements, to maximum infrastructure load – specific risks emerge that require careful management and planning. The need for flexible strategies, such as intensive training, cybersecurity measures, and continuous system audits, helps mitigate the risk of delays, conflicts of interest, and technical problems that could negatively affect production efficiency and consortium profitability.

These barriers emphasize the importance of long-term planning and adaptive strategies to ensure system stability and scalability. Effective platform management requires an approach based on flexibility, readiness to resolve conflicts, and regular assessment of technology and operational procedures. Such actions enable companies not only to minimize downtime and increased operational costs but also to maintain competitiveness in a dynamically changing market, thus achieving higher productivity levels and customer satisfaction.

CONCLUSIONS

The dynamic development of technology, new requirements, new markets around us are driving the development of the entire industry. The most important changes include the digitalization of production processes or the use of artificial intelligence. Large companies are better prepared for such changes. Larger financial resources, more opportunities to obtain credit make it easier for them to decide to use cut-ting-edge technology. However, in the case of SMEs it is no longer so easy, precisely because of limited financial re-sources. Therefore, this type of enterprises is looking for other solutions that would not burden them financially as much.

One idea that facilitates access for small and medium-sized enterprises is the formation of consortiums, platforms for interaction, together with other similar enterprises in the same industry. This makes it possible to distribute expenses among several companies, with benefits for all.

The presented case study demonstrates that the Industry 4.0 concept can be implemented in small and medium sized metalworking companies through:

- the use of automation and robotization of production processes, such as cutting, turning and milling,
- introduction of production management systems (MES) and quality management systems (QMS) to achieve more efficient and flexible manufacturing processes,
- integration of automation and robotics systems with information systems, such as ERP systems, to gain full visibility and control over production processes,
- introduction of industrial networking systems (Industrial IoT) to collect and analyze production data to achieve better product quality and improve process efficiency,
- introduction of digital solutions, such as modeling and simulation of production processes, digital product design, and digital models of machines and production lines.

This is a purely technical aspect, but on the path of transformation, as the example shows, a huge problem is the cultural barrier of changing mindsets in terms of adopting new solutions and technologies, which is a consequence of a lack of knowledge and competence. In addition, for a single entity, the cost of implementing new technologies and Industry 4.0 solutions is often too high for small and medium-sized enterprises. Another problem turned out to be the lack of appropriate standards and regulations that could facilitate the implementation of Industry 4.0 technologies. In the presented case, the transformation brought great success, which unfortunately led to the problem of lack of production capacity to be able to acquire the order portfolio. The development assumptions did not assume that the capacity limit would be reached so quickly.

The strategic assumptions turned out to be underestimated in terms of infrastructure availability and utilization level. Full utilization of the infrastructure was achieved half the time earlier than expected, leading to a crisis situation where the existing infrastructure cannot handle the volume of available orders. The stakeholders faced the challenge of solving the problem by either utilizing similar resources to undertake a similar initiative or pursuing new, independent investments. According to the authors, each solution has its advantages and disadvantages, but a better solution is the implementation of a joint investment. This approach reduces risk and increases the possibility of optimal utilization of existing infrastructure, allowing for a more flexible response to changing conditions in a turbulent environment.

In addition to the technical and organizational requirements for implementing Industry 4.0, there are considerable risks associated with this transformation that companies must consider. For instance, the financial burden of new technologies can be overwhelming, especially for SMEs, and even with cost-sharing mechanisms like consortiums, the unexpected expenses linked to maintenance, training, and system upgrades can strain budgets. The first year of implementation typically brings unforeseen operational issues, from personnel needing intensive training to early stage technical challenges and system instability. These issues underscore the need for contingency planning and accessible technical support to mitigate operational disruptions and keep the project on track.

Furthermore, as the platform matures, new risks emerge related to system flexibility and scalability. By the second year, systems may struggle to keep up with evolving market demands or increased production volumes, particularly if the technology initially chosen lacks adaptability. Additionally, integrated networks are more vulnerable to cybersecurity threats as they become interconnected across firms, raising the importance of robust, regularly updated security measures. Without these, companies could face data breaches or operational shutdowns that can severely impact trust and productivity.

Finally, by the third year, infrastructure capacity can become a major constraint, as seen in the presented case study. Companies may find that their systems have reached maximum operational capacity faster than anticipated, creating a need for rapid expansion or additional investment to handle increased demand. Reaching this threshold not only risks losing new business opportunities but also affects long-term competitiveness. Solutions like joint investments can spread financial and operational risk across multiple companies, offering a more sustainable path for growth and adaptation in a continually evolving industrial landscape.

Research based on a single case study, such as the one described here, has certain limitations that must be taken into account, including:

- Limited generalizability: The results of a case study may not be applicable to other contexts or populations. This is because case studies typically focus on a specific con-text and may not be representative of other settings or situations.
- Bias: The researcher's own biases and subjective interpretations may influence the study's results. For example, a researcher may have a particular view of Industry 4.0, which may affect the data analysis.
- Limited scope: The scope of the study is limited to the specific context being studied. Other factors that may impact the adoption of Industry 4.0 in other contexts may not have been examined in the case study.
- Lack of control: The researcher has limited control over the variables being studied, as they are based on real-world events rather than artificially created scenarios.
- Data collection limitations: The data collection method used in the case study may have limitations, such as relying on self reported data or incomplete records.
- Time limitations: Case studies are often conducted over a limited period of time, which may not provide a full understanding of the situation or the long-term impact of interventions.

Despite these limitations, case studies can be valuable tools for exploring complex phenomena in depth, and can provide insights that may be difficult to obtain through other research methods.

The authors are in constant contact with the all research entities. They want to conduct further research related to the functioning of their cooperation to see what decisions were ultimately made and what effects those decisions had.

ACKNOWLEDGEMENTS

Research and publication were financed by the statutory research fund of the Czestochowa University of Technology.

REFERENCES

[1] N. Beck, D. Rygl, "Categorization of multiple channel retailing in Multi-, Cross-, and Omni-Channel Retailing for retailers and retailing," *Journal of Retailing and Consumer Services*, vol. 27, pp. 170-178, 2015, doi: 10.1016/j.jretconser.2015.08.001.

[2] S. Rezaei, N. Valaei, "Branding in a multichannel retail environment: Online stores vs app stores and the effect of product type," *Information Technology & People*, vol. 30, iss. 4, pp. 853-886, 2017, doi: 10.1108/ITP-12-2015-0308.

[3] B. Ślusarczyk, "Industry 4.0 – Are We Ready?," *Polish Journal of Management Studies*, vol. 17, iss. 1, pp. 232-248, 2018, doi: 10.17512/pjms.2018.17.1.19.

[4] N. Alsaadi, "Modeling and Analysis of Industry 4.0 Adoption Challenges in the Manufacturing Industry," *Processes*, vol. 10, iss. 10, art. no 2150, 2022, doi: 10.3390/pr10102150.

[5] V. Dadi, S. Nikhil, R. Mor, T. Agarwal, S. Arora, "AgriFood 4.0 and Innovations: Revamping the Supply Chain Operations", *Production Engineering Archives*, 2021, vol. 27, iss. 2, pp. 75-89. 2021, doi: 10.30657/pea.2021.27.10.

[6] P. Richnák, H. Fidlerová, "Impact and Potential of Sustainable Development Goals in Dimension of the Technological Revolution Industry 4.0 within the Analysis of Industrial Enterprises", *Energies*, vol. 15, iss. 10, art. no 3697, 2022, doi: 10.3390/en15103697.

[7] J.M. Müller, D. Kiel, K.I. Voigt, "What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability," *Sustainability,* vol. 10, iss. 1, art. no 247, 2018, doi: 10.3390/su10010247.

[8] G. Morteza, "Industry 4.0, digitization, and opportunities for sustainability," *Journal of Cleaner Production*, vol. 252, art. no 119869, 2020, doi: 10.1016/j.jclepro.2019.119869.

[9] L. Sunil, K.M. Sachin, "Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies," *Process Safety and Environmental Protection,* vol. 117, pp. 168-179, 2018, doi: 10.1016/j.psep.2018.04.018.

[10] S.H. Bonilla, H.R.O. Silva, M. Terra da Silva, R. Franco Gonçalves, J.B. Sacomano, "Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges", *Sustainability*, vol. 10, iss. 10, art. no 3740, 2018, doi: 10.3390/su10103740.

[11] B. Grischa, U. André, N. Silke, R. Malte, H. Matthias, "Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes – A literature review," *Journal of Cleaner Production*, vol. 259, art. no 120856, 2020, doi: 10.1016/j.jclepro.2020.120856.

[12] A.M. Braccini, E.G. Margherita, "Exploring Organizational Sustainability of Industry 4.0 under the Triple Bottom Line: The Case of a Manufacturing Company," *Sustainability*, vol. 11, iss. 1, art. no 36, 2019, doi: 10.3390/su11010036.

[13] J. Oláh, N. Aburumman, J. Popp, M.A. Khan, H. Haddad, N. Kitukutha, "Impact of Industry 4.0 on Environmental Sustainability", *Sustainability*, vol. 12, iss. 11, art. no 4674, 2020, doi: 10.3390/su12114674.

[14] K.C. Lin, J.Z. Shyu, K. Ding, "A Cross-Strait Comparison of Innovation Policy under Industry 4.0 and Sustainability Development Transition", *Sustainability*, vol. 9, iss. 5, art. no 786, 2017, doi: 10.3390/su9050786.

[15] A. Kuzior, A. Kwilinski, V. Tkachenko, "Sustainable development of organizations based on the combinatorial model of artificial intelligence," *Entrepreneurship and Sustainability*, vol. 7, iss. 2, pp. 1353-1376, 2019, doi: 10.9770/jesi.2019.7.2(39).

[16] E. Kulej-Dudek, "Ecolabnet service packages as a response to the needs of manufacturing enterprises in the SME sector of the Baltic Sea Region," *Production Engineering Archives*, vol. 27, iss. 4, pp. 265-271, 2021, doi: 10.30657/pea.2021.27.35.

[17] D. Djunaedi, "Building social sustainability of pharmaceutical industry through industry 4.0 implementation," *Polish Journal of Management Studies*, vol. 20, iss. 1, pp. 149-158, 2019, doi: 10.17512/pjms.2019.20.1.13.

[18] E. Oztemel, S. Gursev, A Taxonomy of Industry 4.0 and Related Technologies. In J.H. Ortiz, (Eds.), *Industry 4.0. Current Status and Future Trends*, IntechOpen, UK. London, 2020, pp. 45-65.

[19] F. Chromjakova, Stabilization of Digitized Processes. In J.H. Ortiz, (Eds.), *Industry 4.0. Current Status and Future Trends*, IntechOpen, UK. London, 2020, pp. 85-101.

[20] T.J. Turgeon, "Upgrading strategies for the digital economy", *Global Strategy Journal*, vol. 11i. iss. 1, pp. 34-57, doi: 2019, 10.1016/j.ijpe.2020.107735.

[21] G.B. Benitez, N.F. Ayala, A.G. Frank, "Industry 4.0 innovation ecosystems: an evolutionary perspective on value cocreation," International *Journal of Production Economics*, vol. 228, art. no 107735, 2022, doi: 10.1016/j.ijpe.2020.107735.

[22] M. Wang, R. Zhang, R. Abdulwase, S. Yan, M. Muhammad, "The Construction of Ecosystem and Collaboration Platform for Enterprise Open Innovation," *Frontiers in Psychology*, vol. 13, art. no 935644, 2022, doi: 10.3389/fpsyg.2022.935644.

[23] A.A. Chandio, Y. Jiang, Rehman, M.A. Twumasi, A.G. Pathan, M. Mohsin, "Determinants of demand for credit by smallholder farmers': a farm level analysis based on survey in Sindh, Pakistan," *Journal of Asian Business and Economic Studies*, vol. 29, pp. 225-240, 2022, doi: 10.1108/jabes-01-2020-0004.

[24] K., Melendez, A. Dávila, A. Melgar, "Literature review of the measurement in the innovation management," *Journal of Technology Management & Innovation*, vol. 14, pp. 81-87, 2019, doi: 10.4067/s0718-27242019000200081.

[25] S. King, S.S. Grobbelaar, Industry 4.0 and Business Model Innovation: A Scoping Review. In *Proceedings of the 2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, Cardiff, UK, 15–17 June 2020; pp. 1–8, doi: 10.1109/ICE/ITMC49519.2020.9198424.

[26] B. Brenner, "Transformative sustainable business models in the light of the digital imperative-a global business economics perspective," *Sustainability*, vol. 10, iss. 12, art. no 4428, 2018, doi: 10.3390/su10124428.

[27] M. Krynke, D. Klimecka-Tatar, "The use of Computer Simulation Techniques in Production Management," *Materials Research Proceedings*, vol. 24, pp. 126-133, 2022, doi: 10.21741/9781644902059-19.

[28] S. Pattanapairoj, K. Nitisiri, K. Sethanan, "A Gap Study between Employers' Expectations in Thailand and Current Competence of Master's Degree Students in Industrial Engineering under Industry 4.0," *Production Engineering Archives*, vol. 27 iss. 1, pp. 50-57, 2021, doi: 10.30657/pea.2021.27.7.

[29] L. Bonekamp, M. Sure, "Consequences of Industry 4.0 on Human Labour and Work Organisation," *Journal of Business and Media Psychology*, vol. 6, iss. 1, pp. 33-40, 2015.

[30] M.R.A., Bakar, , N.A.M. Razali, M. Wook, M.N. Ismail, T.M.T. Sembok, "Exploring and Developing an Industrial Automation Acceptance Model in the Manufacturing Sector Towards Adoption of Industry 4.0," *Manufacturing Technology*, vol. 21, iss. 4, pp. 434-446, 2021, doi: 10.21062/mft.2021.055.

[31] S. Erol, A. Jäger, P. Hold, K. Ott, W. Sihn, "Tangible Industry 4.0: A Scenario-Based Approach to Learning for the Future of Production," *Procedia CIRP*, wol. 54, pp. 13-18, 2016, doi: 10.1016/j.procir.2016.03.162.

[32] S. Vaidya, P. Ambad, S. Bhosle, "Industry 4.0 - A Glimpse," *Procedia Manufacturing*, vol. 20, pp. 233-238, 2018, doi: 10.1016/j.promfg.2018.02.034.

[33] M.A.K. Aiman, M.F. Othman, N.H.H. Azli, M.F. Talib, "Industry 4.0: A Review On Industrial Automation And Robotic," *Jurnal Teknologi*, vol. 78, iss. 6-13, 2180-3722, 2016, doi: 10.11113/jt.v78.9285.

[34] J. K. Gerrikagoitia, G. Unamuno, E. Urkia, A. Serna, "Digital manufacturing platforms in the industry 4.0 from private and public perspectives," *Applied Sciences*, vol. 9, iss. 14, art. no 2934, 2019, doi:10.3390/app9142934.

[35] I. Castelo-Branco, F. Cruz-Jesus, T. Oliveira, "Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union," *Computers in Industry*, vol. 107, pp. 22-32, 2019.

[36] S.B. Rane, Y.A.M. Narvel, "Redesigning the business organization using disruptive innovations based on blockchain IoT integrated architecture for improving agility in future Industry 4.0," *Benchmarking: An International Journal*, vol. 28, iss. 5, pp. 1883-1908, 2019, doi: /10.1108/BIJ-12-2018-0445.

[37] K. Witkowski, "Internet of things, big data, industry 4.0 – innovative solutions in logistics and supply chains management", *Procedia Engineering*, vol. 182, pp. 763-769, 2017, doi: 10.1016/j.proeng.2017.03.197.

[38] Y. Wang, H.S. Ma, J.H. Yang, K.S. Wang, "Industry 4.0: a way from mass customization to mass personalization production," *Advances in Manufacturing*, vol. 5, iss. 4, pp. 311-320, 2017, doi: 0.1007/s40436-017-0204-7.

[39] M. Krynke, K. Mielczarek, "Applications of linear programming to optimize the cost-benefit criterion in production processes," MATEC Web of Conferences, vol. 183, art. no 04004, 2018.

[40] A. Efimova, P. Briš, " The implementation of the conjunction of lean six sigma and industry 4.0: a case study in the Czech Republic," *Management Systems in Production Engineering*, vol. 30, iss. 3, pp. 223-229, 2022, doi: 10.2478/mspe-2022-0028.

[41] B. Gajdzik, "Key Directions in Changes from Steelworks 3.0 to Steelworks 4.0 with Analysis of Selected Technologies of Digitalizing the Steel Industry in Poland," *Management Systems in Production Engineering*, vol. 30, iss. 1, pp. 46-53, 2022, doi: 10.2478/mspe-2022-0006.

[42] T. Kellner, M. Necas, M. Kanak, M. Kyncl, J. Kyncl, "Assessment of Readiness for Industry 4.0 Implementation in Ceramic Industry," *Manufacturing Technology*, vol. 20, iss. 6, pp. 763-770, 2020, doi: 10.21062/mft.2020.110.

[43] A. Tubis, K. Grzybowska, "In Search of Industry 4.0 and Logistics 4.0 in Small-Medium Enterprises – A State of the Art Review," *Energies*, vol. 15, iss. 22, art. no 8595, 2022, doi: 10.3390/en15228595.

[44] E. Mezentseva, "Advantages and Barriers of Industry 4.0 Concepts Implementation in Small and Medium Industrial Enterprises," *SHS Web of Conferences*, vol. 93, art. no 01007, 2021, doi: 10.1051/shsconf/20219301007.

[45] M. Brettel, N. Friederichsen, M. Keller, M. Rosenberg, "How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0

Perspective," *International Science Index, Information and Communication Engineering*, vol. 8, iss. 1, pp 37-44, 2014.

[46] G. Orzes, E. Rauch, S. Bednar, R. Poklemba, Industry 4.0 Implementation Barriers in Small and Medium Sized Enterprises: A Focus Group Study. In *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Bangkok, Thailand, 2018, pp. 1348-1352, doi: 10.1109/IEEM.2018.8607477.

[47] E. Rauch, T. Stecher, M. Unterhofer, P. Dallasega, D. Matt, Suitability of Industry 4.0 Concepts for Small and Medium Sized Enterprises: Comparison between an Expert Survey and a User Survey. In *Proceedings of the International Conference on Industrial Engineering and Operations Management*. Bangkok, Thailand, March 5-7, 2019, pp. 1174-1185.

[48] M. Kapler, "Barriers to the implementation of innovations in information systems in SMEs," *Production Engineering Archives*, vol. 27, iss. 2, pp. 156-162, 2021, doi: 10.30657/pea.2021.27.20.

[49] M. Mamad, "Challenges and Benefits of Industry 4.0: an overview," *International Journal of Supply and Operations Management*, vol. 5, iss. 3, pp. 256-265, 2018, doi: 10.22034/2018.3.7.

[50] D. Kuster, N. Prass, Y.-S. Gloy, "Textile Learning Factory 4.0 – Preparing Germany's Textile Industry for the Digital Future," *Procedia Manufacturing*, vol. 9, iss. 214-221, 2017, doi: 10.1016/j.promfg.2017.04.035.

[51] A. Moeuf, R. Pellerin, S. Lamouri, S. Tamayo-Giraldo, R. Barbaray, "The industrial management of SMEs in the era of Industry 4.0," *International Journal of Production Research*, vol. 56, iss. 3, art. no 1118, 2017, doi:10.1080/00207543.2017.1372647.

[52] S. Mittal, M.A. Khan, D. Romero, T. Wuest, "A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)," *Journal of Manufacturing Systems*, vol. 49, pp. 194-214, 2018, doi: 10.1016/j.jmsy.2018.10.005.

[53] A.M. Braccini, E.G. Margherita, "Exploring organizational sustainability of Industry 4.0 under the triple bottom line: The case of a manufacturing company," *Sustainability*, vol. 11, iss. 1, art. no 36, 2019, doi:10.3390/su11010036.

[54] P. Glavič, R. Lukman, "Review of sustainability terms and their definitions," *Journal of Cleaner Production*, vol. 15, iss. 18, pp. 1875-1885, 2007, doi:10.1016/j.jclepro.2006.12.006.

[55] A. Ruggieri, A.M. Braccini, S. Poponi, E.M. Mosconi, "A meta-model of inter-organisational cooperation for the transition to a circular economy," *Sustainability*, vol. 18, iss. 11, art. no 1153, 2016, doi:10.3390/su8111153.

[56] Y.C. Liang, X. Lu, W.D. Li, S. Wang, "Cyber Physical System and Big Data enabled energy efficient machining optimization," *Journal of Cleaner Production*, vol. 187, pp. 46-62, 2018, doi:10.1016/j.jclepro.2018.03.149.

[57] B.Y. Adel, "How Can Industry 4.0 Contribute to Combatting Climate Change," *Revue d'économie industrielle*, vol. 169, pp. 161-193, 2020, doi:10.4000/rei.8911.

[58] J.M. Müller, D. Kiel, K.I. Voigt, "What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability," *Sustainability*, vol. 10, iss. 1, art. no 247, 2018, doi:10.3390/su10010247.

[59] M. Suchacka, "Social Determinants of Conducting Innovative Business Activity in the Opinion of the Inhabitants of the Silesian Voivodeship (Poland)," *System Safety: Human – Technical Facility – Environment*, vol. 5, iss. 1, pp. 359-369, 2023, doi: 10.2478/czoto-2023-0039.

[60] *Industry 4.0 – how to navigate digitization of the manufacturing sector*. McKinsey & Company, 2015.

[61] V. Dolci, B. Bigliardi, A. Petroni, B. Pinia, S. Filippelli, L. Tagliente, "Integrating Industry 4.0 and Circular Economy: A Conceptual Framework for Sustainable Manufacturing," Procedia Computer Science, vol. 232, pp. 1711-1720, 2024, doi: 10.1016/j.procs.2024.01.169.

[62] M. Ghobakhloo, M. Iranmanesh, A. Grybauskas, M. Vilkas, M. Petraitė, "Industry 4.0, innovation, and sustainable development: A systematic review and a roadmap to sustainable innovation," *Business Strategy and the Environment*, vol. 30, iss. 8, pp. 4237-4257, 2021, doi: 10.1002/bse.2867.

[63] M.A. Shabur, "A comprehensive review on the impact of Industry 4.0 on the development of a sustainable environment," *Discover Sustainability*, vol. 5, art. no 97, 2024, doi:10.1007/s43621-024-00290-7.

[64] M. Ingaldi, R. Ulewicz, "Problems with the Implementation of Industry 4.0 in Enterprises from the SME Sector," *Sustainability*, vol. 12, iss. 1, art. no 217, 2022, doi: 10.3390/su12010217.

[65] R. Ulewicz, B. Krstic, M. Ingaldi, "Mining Industry 4.0 – Opportunities and Barriers," *Acta Montanistica Slovaca*, vol. 27, iss. 20, pp. 291-305, 2022, doi: 10.46544/AMS.v27i2.02.

[66] M. Ingaldi, K. Knop, M. Jagusiak-Kocik, R. Ulewicz, Industry 4.0 in the furniture industry – the problematic aspect in implementation. In *14th International Scientific Conference WoodEMA 2021 – the Response of the Forest-Based Sector to Changes in the Global Economy*, Koper, 16 June 2021-18 June 2021, Proceedings, 2021, pp. 207-212.

[67] M. Torchia, A. Calabrò, "Open Innovation in SMEs: A Systematic Literature Review," *Journal of Enterprising Culture*, vol. 27, iss. 2, pp. 201-228, 2019, doi: 10.1142/s0218495819500080.

[68] W. Fu, Q. Wang, X. Zhao, "Platform-based service innovation and system design: a literature review," *Industrial Management & Data Systems*, vol. 118, iss. 5, pp. 946-974, 2018, doi: 10.1108/imds-03-2017-0129.

[69] H. Sikandar, U.H. Abdul Kohar, "A systematic literature review of open innovation in small and medium enterprises in the past decade," *Foresight*, vol. 24, iss. 6, pp. 742-756, 2022, doi: 10.1108/FS-01-2021-0030.

[70] H. Mokter, " A review of literature on open innovation in small and medium-sized enterprises," *Journal of Global Entrepreneurship Research*, vol. 5, iss. 6, pp. 1-12, 2015,doi: 10.1186/s40497-015-0022-y.

[71] V. Venkatesh, S.A. Brown, H, Bala, "Bridging the Qualitative-Quantitative Divide: Guidelines for Conducting Mixed Methods Research in Information Systems," *MIS Quarterly*, vol. 37, iss. 1, pp. 21-54, 2013, doi: 10.25300/misq/2013/37.1.02.

[72] N.L. Leech, A.J. Onwuegbuzie, "A typology of mixed methods research designs," *Quality & Quantity*, vol. 43, iss. 2, pp. 265-275, 2007, doi: 10.1007/s11135-007-9105-3.

[73] B. Wachnik, "Analysis of the use of artificial intelligence in the management of Industry 4.0 projects. The perspective of Polish industry," *Production Engineering Archives*, vol. 28, iss. 1, pp. 56-63, 2022, doi: 10.30657/pea.2022.28.07.

[74] Czakon, W. Eds.; *Podstawy Metodologii Badań w Naukach o Zarządzaniu*. Oficyna Wolters Kluwer Business, Warszawa, Poland, 2011.
[75] David, P. *Key Performance Indicators: Developing, Implementing, and Using Winning KPIs*. John Wiley & Sons Publications. 2007.
[76] A. Moeuf, S. Lamouri, R. Pellerin, S. Tamayo-Giraldo, E. Tobon-Valencia, R. Eburdy, "Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs," *International Journal of Production Research*, vol. 58, iss. 5, pp. 1384-1400, 2020, doi: 10.1080/00207543.2019.1636323.
[77] A. Oraz Raj, G. Dwivedi, A Sharma, A.B.L. de Sousa Jabbour, S. Rajak, "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective," *International Journal of Production Economics*, vol. 224, art. no 107546, 2020, doi: 10.1016/j.ijpe.2019.107546.
[78] V.A. Wankhede, S. Vinodh, " Analysis of barriers of cyber-physical system adoption in small and medium enterprises using interpretive ranking process," *The International Journal of Quality & Reliability Management*, vol. 39, iss. 10, pp. 2323-2353, 2022, doi: 10.1108/IJQRM-06-2021-0174.

Manuela Ingaldi
ORCID ID: 0000-0002-9793-6299
Czestochowa University of Technology
Faculty of Management
ul. Dabrowskiego 69, 42-201 Czestochowa, Poland
e-mail: manuela.ingaldi@pcz.pl

Robert Ulewicz
ORCID ID: 0000-0002-5694-4284
Czestochowa University of Technology
Faculty of Management
ul. Dabrowskiego 69, 42-201 Czestochowa, Poland
e-mail: robert.ulewicz@pcz.pl