

From Industry 4.0 to Supply Chain 4.0 – the Digital Transformation Influencing SCM Processes of Manufacturing Enterprises with ICT Solutions

Marta Starostka-Patyk

Czestochowa University of Technology

Czestochowa, Poland

m.starostka-patyk@pcz.pl

Helena Kościelniak

Calisia University

Calisia, Poland

h.koscielniak@uniwersytetkaliski.edu.pl

Paulina Grunt

Capgemini

Katowice, Poland

paulina.grunt@capgemini.pl

Abstract

Supply Chain 4.0 is the result of the fourth industrial revolution (Industry 4.0). The use of modern technologies and digitalization have become a fact in logistics activities. The development of the Supply Chain 4.0 concept poses a number of new challenges, especially for manufacturing companies that must ensure the efficiency and effectiveness of their processes, also in the area of supply chain management (SCM). The article presents the results of a study aimed at reflecting on the possibilities of investing in modern ICT solutions and digital Supply Chain 4.0 supporting supply chain management processes in Polish and German micro, small and medium-sized enterprises.

Keywords: Supply Chain 4.0, management, micro, small and medium-sized manufacturing enterprises, ICT, digital solutions.

1. Introduction

Industry 4.0, also known as the Fourth Industrial Revolution, is a significant transformation that integrates digital technology into traditional industrial practices, thereby revolutionizing the manufacturing landscape. The core of Industry 4.0 lies in its ability to make manufacturing smarter through automation and data exchange, leading to increased productivity, improved operational efficiencies, and the creation of new business models [12].

Supply Chain 4.0, emerging from the principles of Industry 4.0, represents a transformative shift towards fully digitized, interconnected supply chains that leverage cyber-physical systems, the Internet of Things (IoT), and advanced data analytics [10]. Key features of this new paradigm include predictive analytics for demand forecasting, automated inventory management, and smart logistics that optimize routing and delivery [8], [11].

According to the latest literature review in the area of Supply Chain 4.0, the following ICT and digital solutions are applicable for supporting supply chain management processes in enterprises:

- 1) Artificial Intelligence (AI) and Machine Learning are increasingly utilized to optimize various aspects of supply chain planning. AI systems enhance the efficiency of these processes by automating decision-making and predictive analyses, significantly improving the agility and responsiveness of supply chain operations [18]. Machine Learning techniques are adept at identifying patterns within large data sets [25].
- 2) Augmented Reality (AR) and Virtual Reality (VR) are increasingly applied to support

various processes in warehouse management, such as order picking, packaging, and handling goods. AR enables the superimposition of virtual data over the real-world view, assisting workers in navigating complex warehouse environments and reducing error rates in picking processes [14], [23].

3) Autonomous Vehicles, including autonomous trucks and delivery drones, are revolutionizing the transportation processes within the supply chain. These technologies automate the delivery process, enabling faster and more efficient transportation of goods, particularly in urban areas [21], [22].

4) Big Data and Data Analytics play pivotal roles in enhancing supply chain management by harnessing data generated from various sources. These capabilities streamline operations and contribute to more accurate predictions and better resource allocation, leading to significant cost reductions and enhanced service delivery [4], [1].

5) Blockchain technology can significantly enhance supply chain management by providing a secure and transparent system for tracking transactions and ensuring product authenticity. By utilizing blockchain, stakeholders can achieve greater trust and efficiency, reducing the risk of fraud and improving the overall integrity of the supply chain [7], [27].

6) Cloud Computing and Edge Computing are pivotal technologies in modern supply chain management, facilitating data storage and processing from various sources for monitoring and management purposes. Cloud computing offers robust platforms where large amounts of data can be stored and processed [16]. On the other hand, edge computing processes data on edge devices. This capability is especially beneficial in real-time decision-making and improving the responsiveness of supply chain operations [28].

7) Cybersecurity and Biometric Technologies are increasingly integrated into identity management and ensure safety in manufacturing plants, warehouses, and distribution centers. Biometric technologies, such as fingerprint scanning, facial recognition, and iris scanning, provide robust solutions for secure access control by verifying unique biological traits of individuals. This method enhances security by reducing the risk of unauthorized access and ensuring that only designated personnel can enter sensitive areas or access critical systems [9], [29].

8) The creation of Digital Twins in supply chain elements allows for the simulation of various scenarios and the optimization of logistics operations. Digital Twins can be utilized to monitor and manage the performance of machines, vehicles, and devices in real-time. Digital twins in supply chains can significantly improve response times, increase accuracy in monitoring, and foster proactive maintenance and management, thereby leading to reduced downtime and increased operational efficiency [6], [24].

9) E-commerce platforms and electronic B2B marketplaces significantly facilitate the management of orders, sales, and distribution of products in the supply chain. Additionally, these platforms help in optimizing inventory levels and reducing delivery times, thereby improving overall supply chain performance [5], [13].

10) Industrial Robotics and Automation are transforming supply chain processes by enabling the automation of various tasks. These technologies significantly enhance the efficiency and precision of logistical operations [2], [26].

11) Integrated Enterprise Resource Planning (ERP) systems are pivotal for unifying various enterprise functions, including production, sales, purchasing, warehousing, and accounting. The integration capabilities of ERP systems streamline internal business processes and support broader supply chain management objectives [15], [19].

12) The Internet of Things (IoT) significantly enhances the monitoring and management of various elements within the supply chain, including transportation, warehousing, and production. These capabilities allow for greater control and efficiency in managing supply chain operations [3], [17].

13) Nanotechnology can be employed to create advanced sensors and labels that enable real-time monitoring of product quality and location. This technology allows for the tracking of product origins, ensuring authenticity, and compliance with quality standards.

14) Within the framework of Industry 4.0, Sustainable Supply Chain solutions are gaining increasing importance, focusing on minimizing the environmental impact of production activities. Technologies such as energy consumption monitoring, material recycling, and

optimized delivery routes play a critical role in reducing greenhouse gas emissions and minimizing the carbon footprint [20].

In the contemporary supply chain management, the significance and utility of Information and Communication Technology (ICT) and digital solutions are profound and multifaceted. On their basis, the study presented in the article was developed.

The sheer variety and abundance of modern Supply Chain 4.0 technologies demonstrate a remarkable spectrum of tools designed to enhance efficiency, transparency, and responsiveness within the supply chain operations. Such digital innovations facilitate seamless integration and synchronization across various segments of supply chain activities, empowering organizations to achieve optimized logistical performance and superior decision-making capabilities.

The aim of the article is to check whether manufacturing companies are willing to invest in modern ICT and digital supply chain 4.0 solutions to support their supply chain management processes. It can be assumed that large enterprises have adequate funds for such solutions. Micro, small and medium-sized companies are problematic. Especially since they usually have the largest market share in each country. In order to learn about the current development trends of production enterprises within Supply Chain 4.0 in Logistics 4.0, a survey was conducted among micro, small and medium-sized enterprises from Poland and Germany. Based on the results, it is possible to predict the development of modern technologies in the Supply Chain 4.0 area in business practice. At the same time, they make it possible to fill the identified research gap: lack of detailed information on the possibilities of using ICT and digital Supply Chain 4.0 solutions in supporting supply chain management processes in micro, small and medium-sized production enterprises.

2. Methodology

The research results presented in the article constitute a thematic section of a larger study aimed at obtaining information on the possibilities of implementing modern and digital ICT solutions in the logistics of manufacturing micro, small and medium-sized enterprises. This study was a survey. Its main goal was to assess the chances of implementing modern and digital ICT solutions in the logistics of manufacturing enterprises in the context of the concepts of Logistics 4.0 and Supply Chains 4.0, based on Industry 4.0 development and achievements.

For the purposes of this article, 4 main survey questions were selected for analysis to answer the following research questions:

- *Research question 1:* Which ICT and digital solutions of Supply Chains 4.0 are likely to be implemented to support supply chain management processes in micro, small and medium-sized manufacturing enterprises?
- *Research question 2:* Which ICT and digital solutions of Supply Chains 4.0 that can be implemented to support supply chain management processes are preferred by micro, small and medium-sized manufacturing enterprises?
- *Research question 3:* Do micro, small and medium-sized manufacturing companies see the benefits of the potential implementation of ICT and digital solutions supporting supply chain management processes in relation to the assessment of the logistics strategy and the assessment of profitability changes?

The study was conducted in accordance with the following stages of the research process:

1. Based on comprehensive literature studies related to Industry 4.0, Logistics 4.0, Supply Chain 4.0, and the possibilities of using ICT solutions and digital possibilities in this area, a quantitative survey in the form of a questionnaire was developed. The questionnaire contained 25 main questions, and the final confidential part (4 questions has been chosen to be presented in this paper with their results). A pilot study was carried out on a sample of 10 Polish manufacturing companies to eliminate any ambiguities so that the respondents had no doubts as to whether the questions were unclear. The questionnaire was also evaluated for reliability using the Cronbach Alpha test (values 0.6 to 0.7).
2. In the third quarter of 2022, the main study was carried out among Polish and German production enterprises and information have been gathered with CATI (Computer

Assisted Telephone Interviewing) and CAWI (Computer Assisted Web Interview) methods. The condition for participation in the study was to declare the logistics activities. Participants were also asked not to include the transient turbulence associated with the Covid-19 pandemic in their responses, as this could negatively impact the study's overall results.

3. The adopted research sample was statistically verified as representative of the population of micro, small and medium-sized manufacturing enterprises. 372 manufacturing companies (204 from Poland and 168 from Germany) took part in the study. They were simply randomly selected (it involves the direct and unlimited selection of research units into the statistical sample directly from the general population and without restrictions), and evaluated according to their size based on the level of employees. The sample structure covered: 54.1% micro, 30.3% small, and 15.6% medium-sized manufacturing enterprises.
4. The results of the study were subjected to quantitative analysis with the use of an Excel spreadsheet and Statistica software. In order to elaborate the results, the methods of descriptive statistics, the distance weighted least squares smoothing method, and Mann-Whitney U statistical significance tests were used.

3. Research results

In the survey, respondents from manufacturing companies were asked about planned investments in modern ICT and digital solutions that actively support supply chain management processes, in accordance with the concepts of Industry 4.0 and Supply Chain 4.0. Using the methods of descriptive statistics, the answer to the RQ1 was obtained (Figure 1).

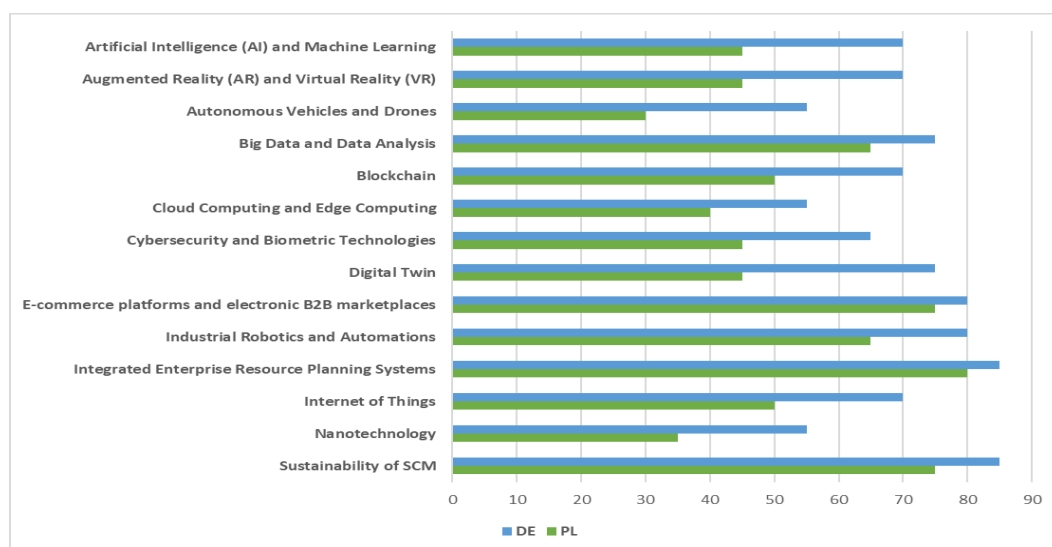


Fig. 1. Percentage indications of declared implementations in the scope of ICT and digital solutions of Supply Chain 4.0 to support supply chain management processes in Polish and German micro, small and medium-sized manufacturing enterprises.

The question had the possibility of multiple-choice. Respondents were to determine the likelihood of investing in the implementation of a given solution supporting supply chain management processes in the medium term (approx. 8 next years).

The analysis of the distribution of responses shows that German manufacturing companies are more positive about investing in ICT and digital solutions supporting supply chain management processes. For all presented options of solutions, German manufacturing companies received a larger number of indications than Polish companies.

German manufacturing companies most often indicated their willingness to invest in Sustainability of SCM, Integrated Enterprise Resource Planning Systems, Industrial Robotics and Automations and E-commerce platforms and electronic B2B marketplaces (80% and more). 70 to 80% of respondents would invest in Digital Twin, Big Data and Data Analysis, Internet of Things, Blockchain, Augmented Reality (AR) and Virtual

Reality (VR) and Artificial Intelligence (AI) and Machine Learning. Less than 70% but more than 50% of German enterprises would also invest in Cybersecurity and Biometric Technologies, Nanotechnology, Cloud Computing and Edge Computing and Autonomous Vehicles and Drones to support their supply chain management processes.

Polish manufacturing enterprises have demonstrated less willingness to invest in analyzed solutions. The greatest interest was shown for investments in Integrated Enterprise Resource Planning Systems, Sustainability of SCM and E-commerce platforms and electronic B2B marketplaces (70-80%). 50% to 70% of these companies indicated investments in Industrial Robotics and Automations, Big Data and Data Analysis, Internet of Things and Blockchain. 40% to 50% of indications were pointed the choice of investment in Digital Twin, Augmented Reality (AR) and Virtual Reality (VR), Artificial Intelligence (AI) and Machine Learning, Cybersecurity and Biometric Technologies and Cloud Computing and Edge Computing. The least investment interest of Polish manufacturing companies was directed at Nanotechnology and Autonomous Vehicles and Drones (less than 40%).

When comparing the indications of Polish and German manufacturing companies, the largest discrepancy is visible in the case of Digital Twin, by 30 percentage points. The smallest discrepancies occur for E-commerce platforms and electronic B2B marketplaces and Integrated Enterprise Resource Planning Systems (5 percentage points).

In general, based on the research results it is visible that manufacturing enterprises from both countries are most willing to invest in Sustainability of SCM, Integrated Enterprise Resource Planning Systems and E-commerce platforms and electronic B2B marketplaces as ICT and digital solutions of Supply Chain 4.0 supporting the supply chain management processes of their companies. The less interest is seen with Cloud Computing and Edge Computing, Nanotechnology and Autonomous Vehicles and Drones.

To answer the RQ2 a non-parametric Mann-Whitney U test of significance of mean differences was used (Tab. 1). It was used to determine whether the differences in assessing the willingness of implementing ICT and digital solutions of Supply Chain 4.0 to support supply chain management processes are statistically significant between selected groups of manufacturing enterprises: the tests compared micro and small, micro and medium, small and medium companies.

The values in the Table 1 indicate the options of ICT and digital solutions of Supply Chain 4.0 supporting the supply chain management processes indicated significantly more often in a given group of manufacturing enterprises, separated on the basis of employment size.

Among the surveyed enterprises, based on the results of the test, there is a visible tendency of small manufacturing enterprises to show a significantly more frequent willingness to invest in modern Supply Chain 4.0 solutions, such as: Artificial Intelligence (AI) and Machine Learning ($Z=4.895$; $p=0.004$), Blockchain ($Z=0.912$; $p=0.434$), Cybersecurity and Biometric Technologies ($Z=3.149$; $p=0.005$), Digital Twin ($Z=2.529$; $p=0.019$), E-commerce platforms and electronic B2B marketplaces ($Z=1.012$; $p=0.378$), Integrated Enterprise Resource Planning Systems ($Z=2.228$; $p=0.038$), and Sustainability of SCM ($Z=1.086$; $p=0.340$) than micro enterprises. At the same time, small enterprises are also more willing to invest in Blockchain ($Z=-1.399$; $p=0.006$), E-commerce platforms and electronic B2B marketplaces ($Z=-0.433$; $p=0.022$), and Integrated Enterprise Resource Planning Systems ($Z=-1.285$; $p=0.049$) than medium-sized companies.

Medium-sized enterprises are significantly more likely to be willing to invest in ICT and digital solutions to support their supply chain management processes in a form of Artificial Intelligence (AI) and Machine Learning ($Z=3.603$; $p=0.008$), Augmented Reality (AR) and Virtual Reality (VR) ($Z=2.151$; $p=0.045$), Big Data and Data Analysis ($Z=4.235$; $p=0.003$), Cybersecurity and Biometric Technologies ($Z=3.046$; $p=0.006$), Internet of Things ($Z=1.417$; $p=0.002$), and Sustainability of SCM ($Z=1.786$; $p=0.001$) than micro companies, and in Big Data and Data Analysis ($Z=3.175$; $p=0.005$), Digital Twin ($Z=0.748$; $p=0.037$), and Sustainability of SCM ($Z=0.222$; $p=0.026$) significantly more often than small companies.

Table 1. The Mann-Whitney U test values and mean evaluations for variables of ICT and digital solutions of Supply Chain 4.0 to support supply chain management processes in small, medium and micro-sized manufacturing enterprises.

Variable	Small/Micro		Medium/Micro		Medium/Small		Mean eval. of enterprise		
	Z	p	Z	p	Z	p	Micro	Small	Medium
1.	4.895	0.004	3.603	0.008	0.163	0.043	3.5	3.1	3.1
2.	0.820	0.525	2.151	0.045	1.621	0.038	3.3	3.2	2.9
3.	1.485	0.177	1.928	0.044	0.709	0.033	3.8	3.7	3.7
4.	0.634	0.614	4.235	0.003	3.175	0.005	3.8	3.7	3.5
5.	0.912	0.434	-1.103	0.032	-1.399	0.006	4.1	3.5	4.8
6.	0.825	0.487	1.033	0.036	0.455	0.047	3.7	3.7	3.7
7.	3.149	0.005	3.046	0.006	0.505	0.037	3.8	3.6	3.6
8.	2.529	0.019	-0.724	0.043	0.748	0.037	3.3	4.4	3.9
9.	1.012	0.378	0.547	0.047	-0.433	0.022	2.1	1.8	2.1
10.	-1.851	0.087	-1.604	0.042	-0.311	0.047	2.4	2.6	2.6
11.	2.228	0.038	0.593	0.044	-1.285	0.049	2.4	2.1	2.4
12.	1.328	0.232	1.417	0.002	0.491	0.018	3.5	3.4	3.3
13.	0.345	0.829	0.991	0.039	0.728	0.049	3.5	3.4	3.4
14.	1.086	0.340	1.786	0.001	0.222	0.026	5.2	4.1	3.9

Z – value of U Mann-Whitney test; p – value of test probability

(1) Artificial Intelligence (AI) and Machine Learning; (2) Augmented Reality (AR) and Virtual Reality (VR); (3) Autonomous Vehicles and Drones; (4) Big Data and Data Analysis; (5) Blockchain; (6) Cloud Computing and Edge Computing; (7) Cybersecurity and Biometric Technologies; (8) Digital Twin; (9) E-commerce platforms and electronic B2B marketplaces; (10) Industrial Robotics and Automations; (11) Integrated Enterprise Resource Planning Systems; (12) Internet of Things; (13) Nanotechnology; (14) Sustainability of SCM

Micro enterprises show the least positive tendencies to invest in ICT and digital solutions of Supply Chain 4.0 supporting the supply chain management processes. The test results indicate that micro companies are more willing to invest in Industrial Robotics and Automations ($Z=-1.851$; $p=0.087$) than small enterprises, and in Blockchain ($Z=-1.103$; $p=0.032$), Digital Twin ($Z=-0.724$; $p=0.043$), and Industrial Robotics and Automations ($Z=-1.604$; $p=0.042$) than medium-sized companies.

For options Autonomous Vehicles and Drones, Cloud Computing and Edge Computing and Nanotechnology, the research test did not reveal any statistically significant differences.

To answer the RQ3 the graphical simulations were carried out using the distance weighted least squares smoothing method (Figure 2).

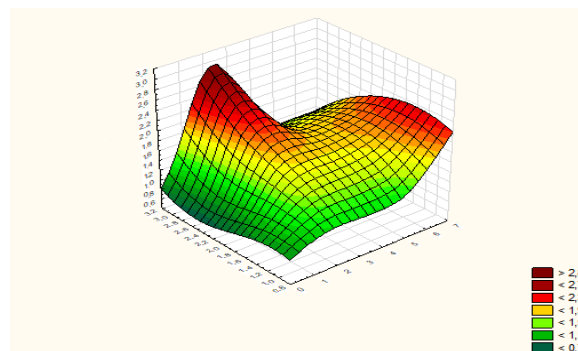


Fig. 2. Simulations of the relationships between the willingness to investment in the implementation of ICT and digital solutions of Supply Chains 4.0 to support supply chain management processes and the assessment of the logistics strategy and the assessment of changes in profitability in manufacturing enterprises.

The simulation of relations signify that with the increase in the assessment of the importance of logistics strategy in manufacturing companies, as well as with the increase in the assessment of profitability changes related to logistics activities, the possible chances of investment in implementation of ICT and digital solutions of Supply Chain 4.0 to support supply chain management processes in these enterprises also increase. Simultaneously, for enterprises with a generally high assessment of the importance of a logistics strategy, the chance of such an investment is slighter in terms of impact.

4. Conclusions

In the survey, respondents from manufacturing companies were asked about planned investments in modern ICT and digital solutions that actively support supply chain management processes, in accordance with the concepts of Industry 4.0 and Supply Chain 4.0. Presented research results indicate a burgeoning interest among micro, small, and medium-sized manufacturing enterprises in investing in cutting-edge technologies within the domain of Supply Chain 4.0. These enterprises recognize the manifold benefits offered by such advancements, including enhanced operational efficiency, improved real-time decision-making, and increased supply chain visibility, which collectively contribute to a more resilient and competitive business model. The promise of these technologies to transform traditional supply chains into dynamic, interconnected systems is acknowledged as a pivotal factor for future business success.

However, despite the recognized potential of Supply Chain 4.0 technologies, the financial aspect of these investments poses a significant challenge for these smaller enterprises. Due to their limited scale and resource constraints, the cost-intensive nature of implementing such technologies often acts as a formidable barrier. This economic hurdle underscores the need for tailored financial strategies and perhaps policy interventions that can facilitate access to these technologies for smaller firms. Providing scalable and affordable technological solutions or financial subsidies could serve as crucial enablers that allow these enterprises to overcome the cost barriers and fully leverage the advantages of digital transformation in the supply chain arena.

Moreover, there are visible positive trends and tendencies in this area, indicating a growing recognition and adaptation among these enterprises. However, it is essential to consider not only the financial aspects but also the time-consuming nature of implementing these solutions. The integration and optimization of Supply Chain 4.0 technologies often require significant time investment for training, system customization, and workflow adjustments. This temporal investment must be factored into the strategic planning processes of these enterprises to ensure a balanced and effective adoption of these transformative technologies. Future research assumes the analysis of technologies that are already implemented by enterprises, along with their tangible benefits in terms of productivity and profitability.

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