Joanna Małecka

http://orcid.org/0000-0002-5017-0417
Poznan University of Technology
joanna.malecka@put.poznan.pl

Monika Grodecka

http://orcid.org/0000-0002-0294-2347
Ignatianum University in Cracow
monika.grodecka@ignatianum.edu.pl

Adam Koliński

http://orcid.org/0000-0002-0467-4673
Poznan School of Logistics
adam.kolinski@wsl.com

Digital Transformation in Logistics: Adoption of Intelligent Technologies and Determinants in Supply Chain Enterprises

Abstract

RESEARCH OBJECTIVE: The aim of the study was to comprehensively assess the level of adaptation of modern logistics technologies and evaluate the significance of key digitalization, market, and process trends, as well as to identify the determinants influencing their implementation in companies of various sizes and business profiles, operating in domestic and international supply chains.

THE RESEARCH PROBLEM AND METHODS: The research problem concerned the identification of digital technologies and trends that exert a dominant influence on the logistics transformation of enterprises, as well as the examination of how their significance varies across different organizational characteristics. A quantitative survey ($N = 121$) was administered, comprising 18 items, 11 of which were evaluated using a Likert scale. The collected data were subjected to descriptive statistical procedures and ranking analysis. The research employed methodologies characteristic of management and quality sciences, as well as political science and administration, which allowed for a multifaceted view of digital transformation processes.

THE PROCESS OF ARGUMENTATION: The argumentation was grounded in comparing the level of logistics technology adaptation with the perception of market and operational trends. The literature on the heterogeneous pace of

521

digital transformation was incorporated and confronted with empirical results, which revealed relationships among analytical, process-oriented, and robotic solutions.

RESEARCH RESULTS: The results indicated that the highest level of adaptation is associated with cloud technologies and Big Data analytics, whereas robotization and blockchain remain at an early stage of implementation. The most influential determinants of development include shifts in consumer behavior, pressure to enhance efficiency, and the necessity to design new processes.

CONCLUSIONS, INNOVATIONS, AND RECOMMENDATIONS: It was found that digital transformation is driven mainly by demand-related and process-oriented factors, while its effectiveness depends on data integration, technological competence development, and efficient acquisition of financial resources. Priority is recommended for investments in analytical technologies and digital competencies, with a cautious approach to robotic and blockchain solutions due to persistent implementation barriers.

INTRODUCTION

Dynamic changes in global supply chains have made logistics one of the key areas of technological transformation. The development of the manufacturing, trade, and service sectors is currently highly dependent on the ability of enterprises to adopt modern digital solutions and integrate them into operational processes. Intensifying market requirements, the increasing complexity of material flows, and pressure to reduce costs and enhance flexibility contribute to the perception of digitalization as a foundation for building resilience and competitive advantage. The logistics sector remains central to this process, as it is in the area of physical and information flow management that digital technologies generate the most measurable outcomes.

The development of the Industry 4.0 and Logistics 4.0 concepts has contributed to the widespread implementation of technologies that were still in the experimental phase a decade ago. Their

presence is now evident in both large international organizations and medium-sized enterprises, which increasingly adopt analytical tools, cloud systems, the Internet of Things, warehouse robotization, and predictive solutions supporting operational decision making. At the same time, numerous studies indicate the uneven nature of this transformation. Not all technologies develop at the same pace, and their level of adaptation depends on several factors, including technological maturity, managerial competencies, access to financial resources and knowledge, and the degree of integration with global supply chains. This phenomenon is observed at both national and international levels.

The evolution of customer and business partner expectations also significantly influences the pace of technology adoption. The growing popularity of e-commerce, shorter order fulfillment cycles, increased demand for personalized services, and expectations for full transparency in delivery processes compel companies to rebuild traditional operating models. Digital transformation is no longer perceived solely as the modernization of IT infrastructure; it is becoming a strategic process requiring the redefinition of processes, structures, modes of collaboration, and business models. As a result, technology is increasingly viewed as a tool enabling the achievement of operational and strategic objectives, although its effectiveness depends on the organization's ability to integrate it purposefully and consistently.

Despite the extensive body of literature on Logistics 4.0, a clear research gap persists concerning the simultaneous analysis of the level of technology adaptation, the significance of digitalization trends, and the determinants of implementation in companies operating in diverse segments of supply chains. Much of the existing research has focused on individual technologies or selected industries, whereas the need for a holistic approach – capturing relationships among technological solutions, market factors, and processes – remains evident. The phenomena under investigation require in-depth analysis in the context of enterprises operating in domestic and international markets and varying in size and business profile.

In view of these conditions, empirical research was undertaken to obtain a deeper understanding of the degree of digitalization and the key factors influencing the implementation of logistics innovations. This objective is multifaceted and includes both an analysis

of the application of modern technologies and an assessment of the significance of trends determining the development directions of contemporary supply chains. Accordingly, and in light of the market changes taking place, the aim of the study was to comprehensively assess the level of adaptation of modern logistics technologies and evaluate the significance of key digitalization, market, and process trends, as well as to identify the determinants influencing their implementation in companies of various sizes and business profiles, operating in domestic and international supply chains.

LITERATURE REVIEW

The literature review on digital transformation and the implementation of smart technologies in logistics was developed on the basis of studies examining both the technological and organizational conditions shaping contemporary supply chains. This approach makes it possible to situate the empirical findings within the current theoretical discourse.

Researchers analyzing the impact of Industry 4.0 on logistics systems, such as Barreto, Amaral, and Pereira, emphasize that the development of digital technologies has become the foundation for supply chain transformation, leading to increased process integration, automation, and improved system interoperability (Barreto et al., 2017). According to Birkel and Müller, the concept of Logistics 4.0 constitutes a response to the growing operational complexity of enterprises and the pressure to incorporate digital technologies (Birkel & Müller, 2021). In turn, research conducted by Wamba, Queiroz, and Trinchery demonstrates that expanding analytical capabilities has become a key source of competitive advantage (Wamba et al., 2020; Queiroz et al., 2020).

Scholars investigating organizational competencies, including Gupta and George, underscore that the ability to work with data constitutes a critical resource for the effective implementation of digital technologies (Gupta & George, 2020). Complementary to this view is the approach represented by Hofmann, who argues that managing data diversity and dynamics is essential for the development of predictive tools (Hofmann, 2019). Other studies indicate that Big

Data analytics enhances operational decision-making, particularly in demand forecasting and route optimization (Tiwari et al., 2018).

A review of the literature on digital supply chains highlights the importance of the synergy between cloud and analytical solutions, which form the backbone of digital transformation in logistics (Büyüközkan & Göçer, 2018). This observation is reinforced by U.S. researchers Hazen, Boone, Ezell, and Jones-Farmer, who identify data quality as the main determinant of analytical system effectiveness (Hazen et al., 2014). According to Wang, Han, and Beynon-Davies, cloud infrastructure reduces entry barriers, enabling enterprises to scale processes and integrate systems more efficiently (Wang et al., 2019).

Automation scholars Bortolini, Faccio, Gamberi, Pilati, and Regattieri argue that the level of robotization across enterprises remains highly diversified and depends on their technological maturity (Bortolini et al., 2020). Other research points out that barriers to robotization and automation arise from high investment costs – including the need to secure adequate financing – a and integration challenges (Ghobakhloo, 2020; Małecka, 2017). Dutch researchers Stoop and van der Togt additionally emphasize the importance of ergonomic and safety factors in warehouse robotization processes (Stoop & van der Togt, 2020).

The findings of French researchers Garnier and Subrin are also noteworthy: they stress that although numerous techniques and tools exist to enhance robot performance through geometric, kinematic, and dynamic modeling, many remain laboratory concepts that do not meet industrial requirements, often being costly, difficult to install, unintuitive, and insufficiently adaptable to real production environments (Garnier & Subrin, 2021). Kshetri points out that blockchain technology possesses significant potential for enhancing transparency, although real world implementations remain scarce (Kshetri, 2018). Kayikci and colleagues identify the main challenges to blockchain adoption, including the lack of standards and low system interoperability (Kayikci et al., 2022). Similarly, Queiroz and Fosso-Wamba argue that despite substantial academic interest, blockchain has not yet reached implementation maturity (Queiroz & Fosso-Wamba, 2019). Min notes that while blockchain has the potential to strengthen supply chain resilience, its adoption is hindered by organizations' limited willingness to share data (Min, 2019).

Studies in retail logistics highlight that shifts in consumer behavior constitute a major driver of logistics process transformation (Hübner et al., 2016). According to Wollenburg, Holzapfel, Hübner, and Kuhn, omnichannel models necessitate process integration and flexible inventory management systems, as expectations concerning speed and service personalization increasingly drive digital innovation (Wollenburg et al., 2018; Ramanathan et al., 2014). Lim and co-authors emphasize that consumer behavior has the strongest influence on the development of last-mile delivery technologies (Lim et al., 2018).

Authorities in supply chain resilience, such as Ivanov and Dolgui, underline that predictive tools are fundamental for building the adaptive capabilities of logistics systems (Ivanov & Dolgui, 2020). This view is echoed in the works of Min and Szozda, who show that predictive systems enhance the quality of strategic and operational decisions, particularly under conditions of high demand volatility (Szozda, 2017; Min, 2010). Predictive solutions also play a key role in inventory management when demand is irregular (Babai et al., 2019).

Researchers of supply chain risk and agility – including Pournader, Shi, Seuring, and Koh – argue that digital technologies reshape the processes of risk identification and management (Pournader et al., 2020). Frederico, Garza-Reyes, Anosike, and Kumar, the authors of the Supply Chain 4.0 maturity model, assert that the success of digital transformation depends on organizational and leadership capabilities. Data-driven systems facilitate more effective integration of activities within supply chains (Frederico et al., 2020; Liu et al., 2021). Moreover, digital transformation scholars stress that technological change requires structural adjustments in organizational architectures and processes. Their studies point to cloud solutions as the basis for integrating industrial and logistics processes in distributed environments (Vial, 2019; Xu et al., 2018).

A synthesis of the reviewed literature indicates that the development of digital technologies in logistics constitutes a multidimensional process shaped by both the availability of IT solutions and the ability of organizations to adapt them. This finding underscores the need for further research into the mechanisms governing the implementation of innovations across diverse operational contexts.

METHODOLOGY

The study was designed as a quantitative survey aimed at determining the level of application of intelligent logistics solutions and identifying key trends and technological needs of companies operating within supply chains. The research instrument was a structured questionnaire consisting of thematic blocks addressing: (1) the use of innovative logistics technologies, (2) the significance of digitalization trends, (3) developments in international trade, (4) software-driven process changes, (5) internal market prospects, (6) process modifications resulting from the development of machinery and robotics, and (7) market needs related to digitalization, automation, and robotization. The survey comprised 18 questions, eleven of which addressed the designated research areas, and respondents evaluated the importance of individual phenomena on a five-point Likert scale (0–5).

The research sample ($N = 121$) included companies representing logistics, transport, trade, manufacturing, and services associated with the flow of goods and information. The demographic characteristics of the surveyed entities indicate a predominance of medium-sized and large enterprises employing more than 250 individuals and operating on the market for more than fifteen years (Figure 1).

Figure 1. Employment and company's age
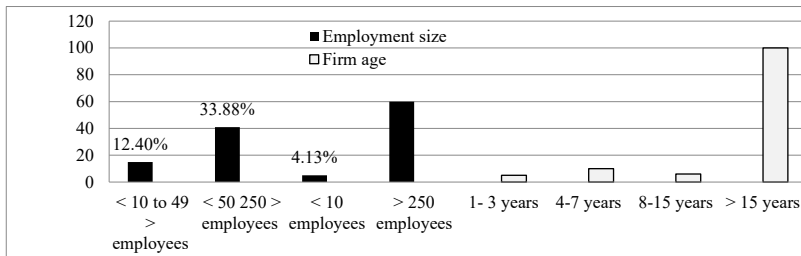
Source: own research.

The sample structure indicates that the responses were provided by organizations with a high level of operational maturity and experience in implementing logistics innovations, meaning that the results reflect technology adaptation in stable and well-established enterprises. The collected data were analyzed using descriptive statistics.

Mean values were calculated for each item, and a ranking analysis identified the highest-rated determinants across the eleven research areas, enabling a comparison of dominant technological and market factors.

To deepen the analysis, cross-sectional tables by company size were developed, allowing the identification of relationships between organizational advancement and the adoption of digital and robotic solutions. Data processing and visualization were carried out in spreadsheet tools using consistent response categories. The all research procedure ensured respondent anonymity and full compliance with social research ethics. The questionnaire was distributed electronically, and participation was voluntary.

RESEARCH RESULT AND DISCUSSION

The study was conducted among companies from various logistics-related sectors, with the sample dominated by organizations with long market experience. As a result, the findings reflect the technological advancement of stable enterprises equipped with established logistics procedures. Most entities had operated for more than fifteen years and were predominantly medium-sized and large companies with greater investment capacity and knowledge of financial instruments.

The results confirmed that most companies were actively implementing modern solutions to optimize logistics operations. The responses indicate a high level of technological awareness and a proactive approach to digitalization, automation, robotization, and information integration. The variation in technology assessments revealed a clear implementation hierarchy. Data-driven and analytical technologies – a such as cloud platforms, APIs, and Big Data tools – a received the highest ratings, while solutions requiring complex infrastructural or organizational integration, including warehouse robotization and blockchain, were used less frequently. This indicates that companies more readily adopt technologies with lower entry thresholds and broader applicability, whereas capital-intensive and structurally demanding solutions progress more slowly and unevenly. This structure of results highlights the differentiated pace

and intensity of digital transformation across individual logistics technologies (Figure 2).

Figure 2. Average adoption level of logistics technologies
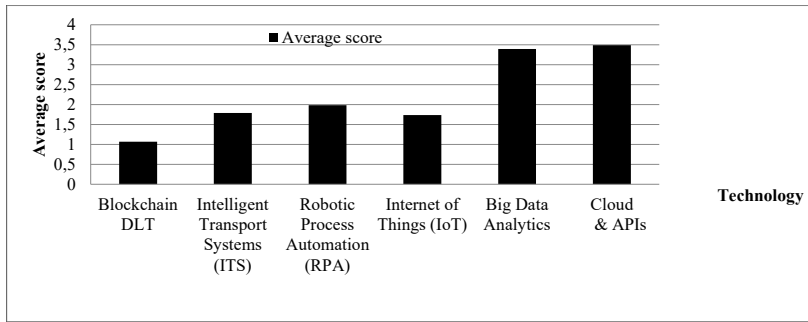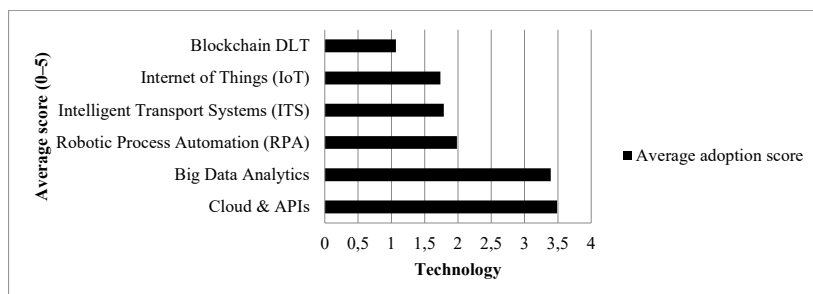

Source: own research.

In the analysis of the degree of application of innovative logistics solutions, the strongest interest and highest levels of implementation were observed for technologies related to Big Data analytics, cloud platforms, and APIs. These findings confirm that such technologies constitute essential tools supporting the digital transformation of the surveyed companies. They enable real-time data collection, storage, and processing, which is particularly valuable in an increasingly volatile market environment. The high intensity of cloud technology usage additionally indicates a shift away from traditional IT architectures based on local servers toward flexible, scalable, and more resilient models.

A noteworthy observation derived from the study is that Big Data technologies and cloud solutions constitute the foundation upon which more advanced predictive, automated, and integrated systems are developed. This indicates that companies prioritize investments in technologies that enhance data quality and processing capabilities, treating them as the basis for subsequent, more complex technological initiatives (Figure 3).

Technologies such as the Internet of Things (IoT), Robotic Process Automation (RPA), and Intelligent Transportation Systems (ITS) received average ratings, indicating that they are in an active implementation phase but require more complex structural and organizational adjustments. IoT adoption depends on process specificity and sensor availability, RPA requires adaptation of the physical operating
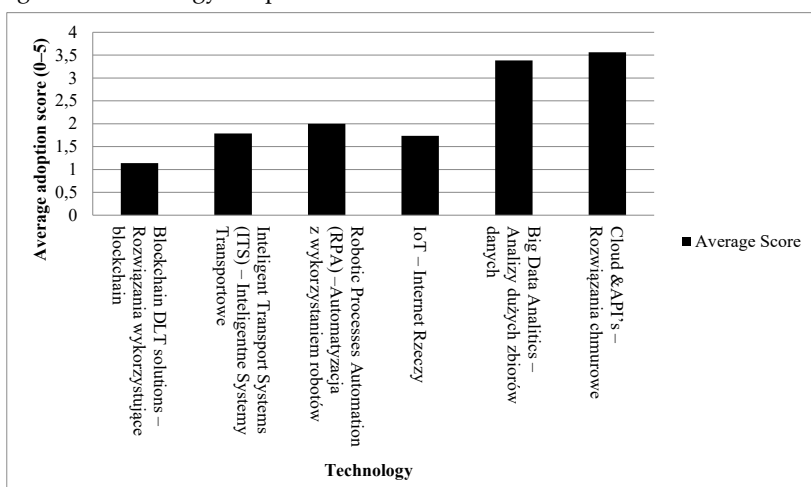
environment, and ITS implementation necessitates cooperation across companies, public institutions, and infrastructure operators.

Figure 3. Ranking of logistics technologies by adoption level

Source: own research.

Figure 4. Technology adoption trends

Source: own research.

Blockchain recorded the lowest level of application, confirming the gap between strong academic interest and limited practical adoption. Low ratings reflect the absence of standards, high integration costs, limited tool maturity, and concerns about interoperability and scalability. Since responses on technology adoption were provided exclusively by large enterprises, comparisons across company size segments are not possible (Figure 4).

The study showed that the most influential trends driving digitalization are changes in consumer behavior and the growing availability of modern technologies. Companies perceive evolving consumption patterns, the rise of e-commerce, and pressure to reduce delivery times as key accelerators of logistics digitalization, supported by the increasing adoption of cloud solutions, integration platforms, and data management systems.

Skilled labor shortages and regulatory changes received moderately high ratings, indicating that enterprises also view automation and digitalization as responses to structural labor market challenges and data protection requirements. The focus on long-term structural factors suggests growing awareness of the need to adapt to shifting goods flows in global supply chains.

Geopolitical trends received lower ratings, likely because they are perceived as difficult to control and exert indirect, delayed effects on logistics operations (Figure 5).

Figure 5. Digitalization trends
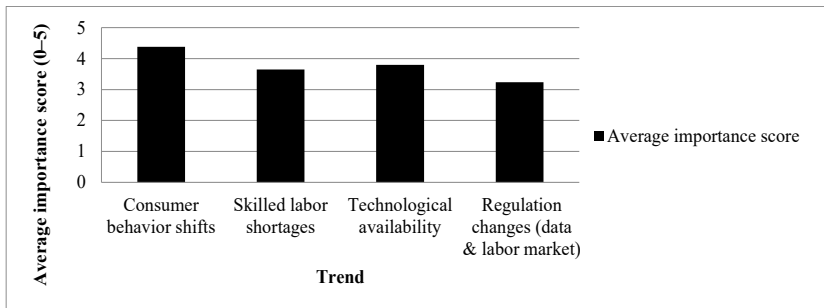
Source: own research.

Another important area of analysis concerned trends related to the development of international trade. The highest ratings were assigned to the internationalization of transport services and the growth of trade between Europe and Asia. This result is consistent with global analyses indicating the increasing share of Asian economies in world trade and the intensive development of intermodal routes, particularly rail and maritime corridors. Moderate importance was attributed to trade wars and the One Belt initiative, which may result from the difficulty companies face in translating geopolitical

dynamics into concrete operational decisions. Significant importance was also assigned to the development of land infrastructure, suggesting that companies recognize the necessity of modernizing transport networks, although the direct impact of such investments on operational activities is perceived as less immediate and less dynamic (Figure 6).

Figure 6. International trade development trends – firms with >250 employees
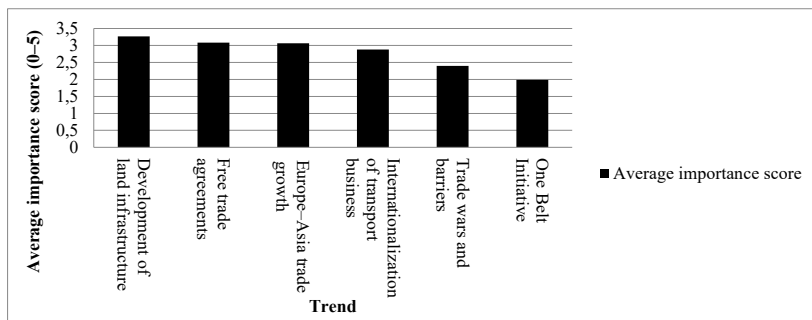
Source: own research.

The trend driven by software development was assigned significant importance, particularly in relation to efficiency pressures and advances in core technologies. High ratings were given to artificial intelligence, the Internet of Things, and data processing technologies, indicating the growing relevance of decision automation and prediction as fundamental components of modern supply chains. Data protection was likewise evaluated highly, which aligns with the increasing importance of cybersecurity in the context of rising cyber threats and the ongoing digitalization of operational data (Figure 7).

In the assessment of trends driven by developments in robotics, the highest ratings were assigned to the advancement of transport-support machinery and electromobility technologies. These findings may be associated with cost pressures and increasing environmental requirements, which compel companies to modernize transport fleets toward more economical and environmentally sustainable vehicles. Lower ratings for fuel price fluctuations and regulatory changes indicate the difficulty of predicting these factors and their relatively limited controllability by enterprises. This suggests that the surveyed

organizations focus primarily on areas subject to direct managerial influence – such as investments in transport technologies – rather than on macroeconomic and political variables characterized by high volatility and uncertainty. The lower importance attached to regulatory factors may also stem from the fact that their effects, although significant, tend to materialize over longer time horizons.

Figure 7. Process change trends
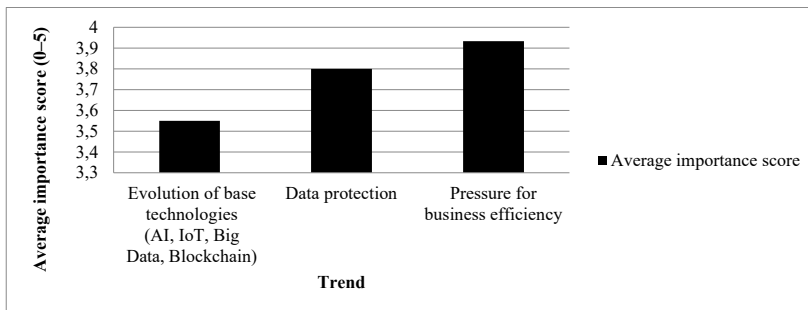
Source: own research.

One of the most important areas of analysis concerned company needs related to digitalization. The highest ratings were given to the design of new processes and new business models. This result confirms that digital transformation is perceived not merely as a change in technological tools but as a comprehensive reconfiguration of organizational functioning, including process restructuring, role redefinition, and the development of new channels of interaction with customers. Significant importance was also attributed to the need for designing new services and sales platforms, which aligns with the global trend toward the development of digital economy platforms. These findings indicate that companies increasingly understand digitalization as a strategic process involving the creation of value-oriented ecosystems and the implementation of data-driven models. The high ratings may additionally reflect rising competitive pressures, which compel companies to seek innovative methods of delivering services and integrating customers into real-time operational processes (Figure 8).

Figure 8. Trends & innovations
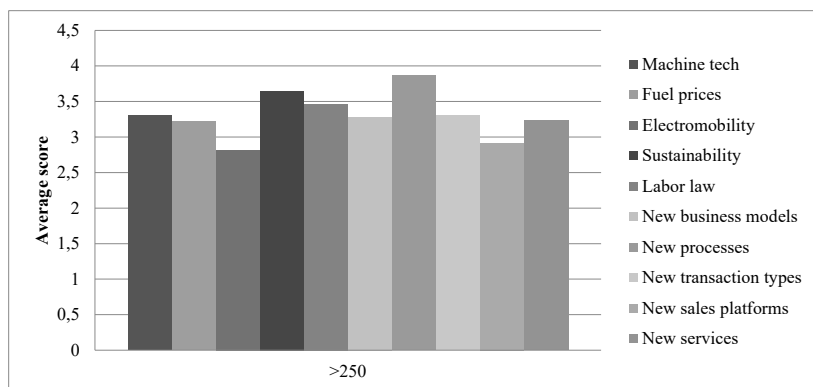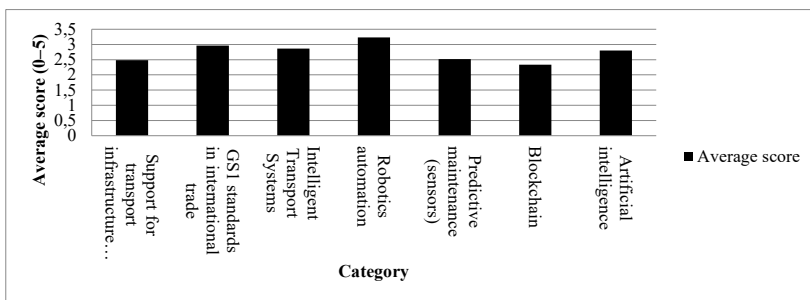

Source: own research.

In the assessment of needs related to the development of international trade, moderate importance was assigned to GS1 standards and infrastructure investments. This indicates that although companies acknowledge their relevance, the urgency of their development is perceived as lower than that of digitalization-related needs. It may therefore be concluded that information flow processes currently represent a higher priority for enterprises than physical flow processes.

In contrast, in the analysis of needs associated with software-driven process changes, the greatest importance was attributed to intelligent transport systems, robotization, and artificial intelligence. These findings are consistent with global supply chain development trends, in which automation, prediction, and real-time data integration play a pivotal role. Blockchain technologies once again received the lowest ratings, confirming that the logistics sector is not yet prepared for their widespread implementation (Figure 9).

Trends affecting the internal market were assigned particular importance in relation to the development of e-commerce and changing buyer behavior. The surveyed companies recognize that these changes not only contribute to the growth of material flows but also necessitate transformations in warehousing, inventory management, and last-mile logistics. The results confirm a global trend toward the automation of picking and storage processes and the increasing need to develop specialized supply management systems under

conditions of volatile and unpredictable demand. It may be assumed that the growing popularity of online shopping additionally supports the development of distribution infrastructures based on decentralized models, such as micro-logistics centers and urban warehouses. These developments also require deeper integration between enterprise and customer IT systems, which increases the importance of tools enabling real-time order monitoring. Companies are likewise compelled to enhance operational flexibility to adapt to the rapid demand fluctuations characteristic of digital sales channels. The findings suggest that the internal market is becoming a major driver of process transformation, stimulating the creation of more responsive and scalable logistics models.

Figure 9. Market actions & innovations

Source: own research.

In the assessment of needs arising from internal market changes, the highest ratings were given to logistics prediction, confirming the growing importance of data analytics in supply chain optimization. Predictive tools enable the anticipation of disruptions, resource planning, and decision-making under uncertainty, representing a fundamental dimension of digital transformation. Technologies supporting e-commerce and consulting related to evolving customer behavior also received high ratings, underscoring the strategic role of digital channels. These correlations demonstrate that internal market development constitutes a strong stimulus for investment in technologies that enhance the speed, flexibility, and transparency of logistics operations, thereby intensifying the dynamics of digital transformation within enterprises (Figure 10).

Figure 10. Internal Market Trends & Services
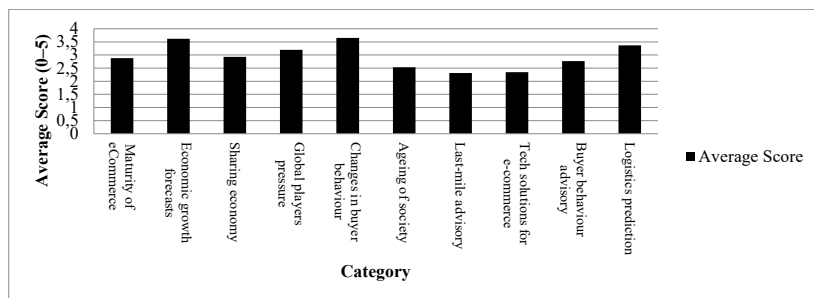
Source: own research.

In the final area concerning robotics needs, the highest ratings were assigned to warehouse robotization and AR/VR solutions supporting warehouse processes. This result indicates that companies recognize the necessity of automating internal warehouse operations, particularly in the context of increasing order volumes and pressure to shorten lead times. Lower ratings for last-mile automation may be associated with the greater complexity of distribution processes and existing infrastructural constraints. The observed preferences may also stem from the fact that warehouse environments are among the most amenable to standardization and technical unification, which enables the implementation of robotic solutions in a more predictable, controllable, and scalable manner. Moreover, AR/VR technologies are perceived as tools with a relatively low entry threshold, supporting both training and operational activities, which further increases their attractiveness for implementation.

In contrast, significant regulatory, urban planning, and organizational barriers continue to impede the robotization of last-mile distribution, slowing the pace of adoption of this category of solutions. The robotization of last-mile logistics requires extensive cooperation among companies, local authorities, and infrastructure operators, which considerably increases the complexity of implementation processes. The diversity of assessments therefore indicates that robotic technologies develop sequentially – first in areas with the highest degree of process controllability, and later in areas requiring complex ecosystem level changes.

In summary, the results of the study indicate a high level of technological awareness among companies and an advanced readiness to implement digital solutions. The greatest implementation activity is concentrated around technologies related to data and its processing, whereas technologies requiring complex cooperation structures, such as blockchain, remain at a relatively early stage of adoption. Market trends – such as the development of e-commerce, changes in buyer behavior, and competitive pressure – clearly shape corporate technology strategies, while operational needs focus on prediction, robotization, and the digital integration of logistics processes. These findings confirm that technological development in the logistics sector is dynamic yet highly differentiated, which poses challenges for enterprises in terms of the consistent and strategic management of digital transformation (Table 1).

Table 1. Top-ranked determinants

Lp.	Question (English)	Top Answer	Average Score
1	Use of innovative logistics solutions	Cloud & APIs – Cloud-based solutions	3.49
2	Importance of digitization trends	Changes in consumer behaviour	4.33
3	Importance of international trade development trends	Development of land-based infrastructure	3.41
4	Importance of softwaredriven process changes	Pressure for business efficiency	4.12
5	Importance of internal market trends	Optimistic forecasts of economic growth	3.63
6	Importance of machine/robotdriven process changes	Focus on environmentally sustainable development	3.64
7	Market needs related to digitization	Design of new processes	4.06
8	Market needs related to international trade development	Implementation of GS1 standards in international trade	3.07
9	Market needs related to software-driven process changes	Automation using robots	3.09
10	Market needs related to internal market changes	Prediction in logistics	3.35
11	Market needs related to machine/robot process changes	Warehouse robotization	2.74

Source: own research.

The table summarizes the highest-rated determinants for each of the eleven research questions, indicating the dominant technological and market areas identified by the surveyed companies. The results demonstrate that the greatest significance is attributed to trends related to digitalization and organizational processes – particularly changes in consumer behavior (4.33), pressure for business efficiency (4.12), and the design of new processes (4.06). In the area of technological innovation, cloud solutions received the highest rating (3.49), confirming their role as key enablers of logistics development.

In the context of international markets, companies emphasized the importance of developing land infrastructure (3.41) and implementing GS1 standards (3.07). In the field of automation and robotization, predictive capabilities in logistics (3.35) and robot-based automation (3.09) were considered significant. The lowest rating was recorded for warehouse robotization (2.74), which may indicate the early stage of adoption of these solutions or investment constraints limiting their development.

Overall, the findings indicate that companies focus primarily on digital and process-oriented solutions, whereas advanced robotization remains an area with a comparatively lower level of implementation.

CONCLUSION AND RECOMMENDATIONS

The results indicate that digitalization in logistics enterprises is advanced, although the implementation of individual technologies remains highly differentiated. Technologies related to data collection, processing, and integration – particularly cloud solutions (3.49) – received the highest ratings, while changes in consumer behavior (4.33) and pressure for business efficiency (4.12) were identified as the most influential market factors. Digital transformation is thus primarily understood as the ability to analyze information and adapt logistics operations to dynamic market conditions.

Technologies requiring complex technical or organizational integration remain at earlier stages of adoption. Low ratings for warehouse robotization (2.74), moderate ratings for robotic automation (3.09), and limited blockchain use confirm persistent investment,

competency, and standardization barriers. Companies focus mainly on demand-driven trends, especially those related to speed, flexibility, and transparency, with the design of new processes (4.06) viewed as a central element of organizational restructuring. Market needs emphasize predictive solutions (3.35), data-integration tools, and technologies enabling automation of warehouse and transport processes, reflecting growing recognition of data-driven decision-making.

The ranking results show a clear distinction between highly rated process-oriented technologies and the slower adoption of capital-intensive physical automation. Consequently, enterprises should prioritize analytical and cloud technologies, strengthen competencies in system integration and data analytics, and approach robotic implementations gradually through pilot projects and cost-benefit analyses.

The study confirms that digital transformation progresses at different rates across information and physical automation technologies and that demand-related factors – particularly consumer behavior – are key drivers of logistics development. A gap between theory and practice in blockchain adoption highlights the need for further research on implementation barriers and inter-organizational cooperation.

The findings should be interpreted with caution due to methodological limitations, including a sample dominated by large, mature enterprises and reliance on self-reported data, which may not fully reflect actual implementation challenges.

References

Babai, M.Z., Ali, M.M., Boylan, J.E., & Syntetos, A.A. (2019). Forecasting and inventory management: *A review and classification. International Journal of Production Economics*, *209*, 15–26.

Barreto, L., Amaral, A., & Pereira, T. (2017). Industry 4.0 implications in logistics: An overview. *Procedia Manufacturing*, *13*, 1245–1252.

Birkel, H., & Müller, J. (2021). Potentials of Industry 4.0 for supply chain management within the triple bottom line of sustainability. *International Journal of Production Economics*, *234*, 107969.

Bortolini, M., Faccio, M., Gamberi, M., Pilati, F., & Regattieri, A. (2020). Automated object recognition in logistics: A literature review. *International Journal of Production Research*, *58*(9), 2713–2736.

Büyüközkan, G., & Göçer, F. (2018). Digital supply chain: Literature review and a proposed framework. *Computers in Industry*, *97*, 157–177.

Frederico, G.F., Garza-Reyes, J.A., Anosike, A., Kumar, V. (2020). Supply chain 4.0: Concepts, maturity and research agenda. *Technological Forecasting and Social Change*, *161*, 120276.

Garnier, S., & Subrin, K (2021). A metrological device for robot identification. *Robotics and Computer-Integrated Manufacturing*, *73*, 102249.

Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for logistics. *Journal of Manufacturing Technology Management*, *31*(5), 977–997.

Gupta, M., & George, J.F. (2020). Toward the development of a big data analytics capability. *Information & Management*, *57*(1), 103124.

Hazen, B.T., Boone, C.A., Ezell, J.D., & Jones-Farmer, L.A. (2014). Data quality for data science, predictive analytics, and big data. *International Journal of Production Economics*, *154*, 72–80.

Hofmann, E. (2019). Big data and supply chain decisions: The impact of volume, variety and velocity properties on the quality of analytics. *Production Planning & Control*, *30*(2–3), 119–128.

Hübner, A., Wollenburg, J., & Holzapfel, A. (2016). Retail logistics in omni-channel retailing: A literature review. *International Journal of Physical Distribution & Logistics Management*, *46*(6–7), 586–605.

Ivanov, D., & Dolgui, A. (2020). Viable supply chain models in the context of industry 4.0. *International Journal of Production Research*, *58*(10), 2904–2925.

Kayikci, Y., Subramanian, N., Dawood, S.R., & Göl, H. (2022). Subsidies in air transport markets: The economic consequences of choosing the wrong mechanism. *Transportation Research Part E: Logistics and Transportation Review*, *160*, 102659.

Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management challenges. *International Journal of Information Management*, *39*, 80–89.

Lim, S.F.W.T. et al. (2018). Last-mile delivery challenges for multi-channel retailers. Business *Strategy and the Environment*, *27*(7), 1193–1206.

Liu, C., Shang, G., Shao, X. (2021). Data-driven supply chain coordination. *Decision Support Systems*, *144*, 113500.

Małecka, J. (2017). Alternative Securities Markets as Financing Sources for SMEs – Selected Aspects of AIM and NC. *Contemporary Issues in Business, Management and Education*, 393–401.

Min, H. (2010). Artificial intelligence in logistics and supply chain management: Theory and applications. *International Journal of Logistics Research and Applications*, *13*(1), 13–39.

Min, H. (2019). Blockchain technology for enhancing supply chain resilience. *Business Horizons*, *62*(1), 35–45. DOI: 10.1016/j.bushor.2018.08.012

Pournader, M., Shi, Y., Seuring, S., & Koh, S. (2020). Blockchain applications in supply chains: A systematic review. *International Journal of Operations & Production Management*, *40*(4), 469–487.

Queiroz, M.M., & Fosso-Wamba, S. (2019). Blockchain adoption in supply chain management: Credibility, transparency and traceability. *International Journal of Information Management, 46*, 38–52.

Queiroz, M.M., Telles, R., & Bonilla, S.H. (2020). *Blockchain and supply chain integration: A systematic review. Transportation Research Part E: Logistics and Transportation Review*, *138*, 101967.

Ramanathan, U., Ramanathan, R., & Ko, L.W.L. (2014). Adoption of e-commerce and consumer behaviour: An empirical study. *Expert Systems with Applications*, *41*(18), 8493–8502.

Stoop, P.P., van der Togt, R. (2020). Adoption barriers and enablers of warehouse robotics. *Safety Science*, *127*, 104706.

Szozda, N. (2017). Forecasting in supply chains: Review and research agenda. *Operations Research and Decisions*, *27*(2), 73–94. DOI: 10.5277/ord170205

Tiwari, S., Wee, H.M., & Daryanto, Y. (2018). Big data analytics in supply chain management: A review. *Computers & Industrial Engineering*, *115*, 319–332.

Vial, G. (2019). Understanding digital transformation: A review and research agenda. *MIS Quarterly*, *43*(1), 3–31.

Wamba, S.F., Queiroz, M.M., & Trinchera, L. (2020). Dynamics between big data analytics capabilities and firm performance. *Information & Management*, *57*(3), 103200.

Wang, Y., Han, J.H., & Beynon-Davies, P. (2019). Understanding block-chain adoption in supply chains. *Technological Forecasting and Social Change, 152*, 119963.

Wollenburg, J., Holzapfel, A., Hübner, A., & Kuhn, H. (2018). Customer preferences in omnichannel retailing. *International Journal of Physical Distribution & Logistics Management, 48*(4), 415–433.

Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2018). Industry 4.0 and cloud-based manufacturing systems: A review. *Robotics and Computer-Integrated Manufacturing, 54*, 1–12.