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Industria mobilis: Integrating cyber-physical systems, data fusion, and autonomous robotics in Slovak Industry 4.0

Marek Nagy

Department of Economics, Faculty of Operation and Economics of Transport and Communications, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovakia

marek.nagy@uniza.sk

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Abstract: *Research Background*: Globalisation and rapid technological change are reshaping manufacturing and trade. Industry 4.0, underpinned by cyber-physical production systems, the Internet of Things (IoT), and artificial intelligence, is pivotal to this transformation. In Slovakia, the automotive sector is a national export pillar, while small and medium enterprises (SMEs) underpin the economy. Recent studies have separately examined advanced vision and sensing in automotive production, wireless networks and smart manufacturing for export growth, and barriers to AI and robotics adoption in SMEs. However, an integrated analysis of how these digital innovations collectively drive Slovak Industry 4.0, spanning both the automotive value chain and SME contexts, is lacking. *Purpose of the article:* This article consolidates and extends findings from three prior manuscripts to provide a unified, in-depth examination of Industry 4.0 applications in Slovakia. We analyse how computer vision, remote sensing, and data fusion enhance automotive manufacturing and supply chains; how wireless and cyber-physical systems accelerate export value-add; and how machine intelligence and autonomous robotics address SMEs' operational gaps. The goal is to deepen the analysis of digital transformation in Slovak industry, identify synergies and shortfalls, and propose strategic directions. *Methodology:* We conducted a comprehensive secondary data analysis and case study synthesis. Data sources included governmental and EU statistics, industry reports, and prior survey data. We re-examined datasets from all three studies, including Slovak export and value-added statistics, foreign direct investment (FDI) structures, and

Corresponding author: *Mohammed Boutouil*
E-mail: *mohammed.boutouil@usmba.ac.ma*

automobile manufacturer supply-chain data, combining statistical and visual analysis techniques. Graphical analytics from the previous case study of PSA Group Slovakia were retained (supply-chain graphs for Citroën C3 and Peugeot 208 vehicles), and new charts were created from the same data (e.g., bar charts of FDI by sector and country). All original tables and figures are preserved for reference. We also synthesised qualitative insights from literature reviews across global value chains, Industry 4.0 frameworks, and SME adoption studies. *Findings and value added:* The analysis reveals that advanced sensing, AI, and network technologies can substantially raise Slovakia's export value-added. In the automotive sector, Industry 4.0-driven computer vision and IoT platforms are integral to smart factories and connected vehicle networks. Slovakia ranks second in added value for key car models, but its national R&D base lags, threatening future competitiveness. Wireless networks and cyber-physical systems are shown to accelerate high-value exports, particularly in the automotive sector, but Slovakia's integration level (DESI index) is moderate. For SMEs, deep learning and robotics promise process optimisation, but financial and skills gaps hinder adoption. Notably, the lack of skilled labour is cited as a more critical barrier than financing for SMEs. This synthesis highlights that combining Industry 4.0 elements, from autonomous vision and data fusion in cars to smart manufacturing networks, can generate new sources of competitiveness, but requires coordinated investment in R&D, workforce development, and supportive innovation policies. The value of this contribution is an original, holistic framework linking Industry 4.0 technologies with value chain enhancement in the Slovak context, along with concrete policy and managerial recommendations (e.g., establishing an "Intelligent Industry Platform" and targeted innovation incentives).

Keywords: Industry 4.0, digital transformation, cyber-physical systems, value-added trade, computer vision

Sustainable Development Goals (SDGs): SDG 7: Affordable and Clean Energy; **SDG 9:** Industry, Innovation and Infrastructure; **SDG 13:** Climate Action

1. Introduction

Slovakia's economy is deeply embedded within global value chains, where the automotive industry has emerged as its most prominent linchpin and a critical engine of export-led growth. Since 2007, the country has maintained its position as the world leader in cars produced per capita, reflecting an extraordinary capacity for large-scale assembly production. This dominance underscores Slovakia's strategic importance as a hub in multinational manufacturing networks, where global automotive giants such as Volkswagen, Kia, Peugeot-Citroën, and Jaguar Land Rover have established primary operations. Nevertheless, beneath this surface-level success lies a structural challenge: the Slovak industrial model remains predominantly assembly-focused, with limited retention of high-value-added activities such as R&D, advanced design, and intellectual property creation.

As a result, while the volume of output is impressive, its contribution to national added value is relatively constrained, leaving the economy vulnerable to external shocks, shifts in global demand, and technological disruptions. In parallel, small and medium-sized enterprises (SMEs), the backbone of Slovak commerce and a cornerstone of employment and regional development, are facing intensifying pressures in an increasingly competitive global landscape. These firms, which account for more than 99% of all businesses in Slovakia, often lack the scale, financial resources, and technological capabilities required to participate effectively in the innovation-driven segments of value chains. Global megatrends such as digitisation, automation, and sustainability, combined with sudden disruptions like the COVID-19 pandemic, have further amplified the need for SMEs to modernise their operations and adapt to rapidly changing market conditions. For both large multinational corporations and domestic SMEs, the capacity to integrate advanced technologies and build resilience has become a decisive factor for long-term competitiveness. Against this backdrop, the emergence of Industry 4.0, the so-called "fourth industrial revolution," represents a transformative paradigm shift for manufacturing and related industries. Rooted in the convergence of physical and digital systems, Industry 4.0 envisions fully networked, intelligent manufacturing environments capable of real-time optimisation and autonomous decision-making. Core enabling technologies include the Internet of Things (IoT) for pervasive data collection and machine-to-machine communication, cloud and edge computing for distributed processing power, artificial intelligence (AI) and machine learning for predictive analytics and process optimisation, and autonomous robotics for adaptive, flexible production lines. Together, these innovations hold the promise of redefining traditional production systems, enabling firms to achieve unprecedented levels of productivity, efficiency, and customisation. They also align with broader sustainability goals by supporting resource-efficient manufacturing and circular economy practices. However, implementing Industry 4.0 technologies is neither automatic nor uniformly beneficial. Empirical evidence highlights significant variation in adoption rates and impacts across sectors, regions, and firm sizes.

While large multinational enterprises often have the financial and organisational resources to invest in advanced digital infrastructure, SMEs face considerable barriers, including capital constraints, skills shortages, and limited awareness of technological benefits. Moreover, the systemic integration of these technologies requires complementary investments in human capital, regulatory frameworks, and national digital infrastructure. As such, the transition to Industry 4.0 is not merely a technological endeavour but also an organisational and policy challenge. In the Slovak context, recent research has begun to explore specific facets of this evolving industrial landscape. Nagy and Lăzăroiu (2022), for instance, examine the deployment of computer vision systems and data fusion techniques in Slovak automotive supply chains. Their analysis reveals considerable potential for value capture through enhanced process monitoring and quality assurance, but also points to persistent weaknesses in domestic R&D capabilities that limit the diffusion of innovation throughout the local ecosystem. Building on this, Valaskova et al. (2022) focus on the integration of wireless and cyber-physical manufacturing systems in Slovakia's automotive export sector. They argue that embracing Industry 4.0 technologies is crucial to sustaining the country's trade competitiveness, especially amid global supply chain reconfigurations and the growing importance of digital trade. Extending the discussion beyond large corporations, Nagy et al. (2023) investigate the readiness of Slovak SMEs to adopt advanced technologies such as smart robotics and deep learning. Their findings highlight a range of obstacles, including financial limitations, technological complexity, and a shortage of skilled personnel, which are key impediments to Industry 4.0 adoption. Despite these valuable contributions, an important gap persists in the literature: no integrated framework unites these disparate strands of research to provide a comprehensive understanding of how Industry 4.0 technologies and supporting infrastructures collectively reshape the Slovak industrial landscape. Specifically, there is a need to examine how high-capital automotive multinationals and resource-constrained domestic SMEs can be aligned within a coherent national strategy for digital transformation. Moreover, critical questions remain unanswered: What are the systemic interactions between enabling technologies such as algorithm-driven sensing (e.g., computer vision, remote mapping), connectivity infrastructures (e.g., 5G, IoT networks), and autonomous robotics/AI in the creation of smart manufacturing networks? How can Slovakia leverage its existing strengths in automotive assembly to transition toward higher-value-added activities and reduce its technological dependency on external actors? Moreover, what policy interventions or organisational innovations are required to ensure that the benefits of Industry 4.0 adoption are distributed equitably across firms of varying sizes and capabilities?

This article seeks to address these pressing questions by synthesising and extending insights from the aforementioned studies. We adopt a systems perspective to explore how core technologies of Industry 4.0 co-evolve within the Slovak industry and how firm-level characteristics and macroeconomic factors influence their adoption patterns. To enrich this analysis, we incorporate original data sources, including export statistics, foreign direct investment (FDI) trends, survey responses from industry stakeholders, and detailed case studies of Slovak manufacturers. This integrative approach enables us to contextualise technological adoption within broader trade and investment dynamics while providing a nuanced understanding of firm-level adaptation strategies. The contributions of this consolidated study are twofold. First, we propose a comprehensive Industry 4.0 roadmap for Slovakia, mapping the trajectory from factory-floor automation to integration within global digital trade networks. This roadmap highlights key technological, organisational, and policy levers for advancing national competitiveness in the era of intelligent manufacturing. Second, by cross-referencing and re-analysing datasets from prior studies, we significantly deepen the analytical scope of existing research. Our meta-analytic approach yields novel insights, including cross-sectoral comparisons, enhanced visualisation of adoption trends, and identification of structural bottlenecks that hinder the diffusion of Industry 4.0. The result is a journal-ready discourse on "Industry 4.0 in motion" (Industria Mobilis) within the Slovak economic context, synthesising existing knowledge and generating actionable recommendations for policymakers and business leaders.

The article is organised as follows. The literature review provides a theoretical foundation by synthesising scholarship on global value chains, successive industrial revolutions, and the emergence of digital manufacturing paradigms. The methodology section outlines our combined secondary data analysis and case study approach, detailing how quantitative and qualitative data were triangulated to ensure robustness. The results present data-driven findings, including statistical and graphical analyses, on export performance, value-added creation, and the deployment of Industry 4.0 technologies across firm types and sectors. The discussion interprets these findings in light of Industry 4.0 theory and contextual constraints, offering strategic insights for scaling digital transformation. Finally, the conclusion summarises key insights and proposes policy and organisational actions to strengthen Slovakia's position in the global manufacturing ecosystem.

2. Literature review

2.1. Global value chains and the foundations of Industry 4.0

The term *Industry 4.0* (I4.0), first introduced at the Hannover Messe in 2011 by Bosch and subsequently formalised within Germany's strategic high-tech programme in 2013, signifies a profound paradigm shift in industrial production brought about by the convergence of digital, physical, and virtual systems (Kagermann & Wahlster, 2011). Widely regarded as the Fourth Industrial Revolution, it follows a historical trajectory of transformative technological epochs: the mechanisation of the 18th century, mass production and electrification in the 19th century, and the advent of electronics and automation in the late 20th century (Kamble et al., 2020; Khan et al., 2021). At its core, Industry 4.0 embodies the intelligent integration of cyber-physical systems (CPS), the Internet of Things (IoT), and artificial intelligence (AI) within manufacturing environments. This integration enables the emergence of "smart factories" that operate in real time, characterised by high levels of autonomy, self-optimisation, and adaptive decision-making (Lin et al., 2023; Luu et al., 2024). The Institute for Systems Automation (ISA) frames this evolution as a "paradigmatic transformation" in production control and enterprise operations, in which traditional linear workflows are replaced by interconnected, data-driven ecosystems capable of dynamically responding to market and environmental changes (Chang et al., 2019; Faria et al., 2022).

2.2. Technological pillars of Industry 4.0

Industry 4.0 encompasses a highly sophisticated constellation of advanced technologies that together reconfigure the logic, structure, and execution of contemporary manufacturing systems. At its core, this paradigm integrates digital and physical infrastructures to enable production systems that are not only highly automated but also context-aware, adaptive, and self-optimising. Foremost among these enabling technologies is the Internet of Things (IoT), which establishes a ubiquitous network of interconnected devices, sensors, and actuators embedded across manufacturing environments. IoT provides the infrastructure for digitising physical assets and processes by enabling seamless data capture, transmission, and real-time interpretation. This pervasive connectivity allows production systems to transcend traditional limitations, supporting granular monitoring of machine health, environmental conditions, and supply chain dynamics. In doing so, IoT facilitates decentralised decision-making, adaptive process control, and the creation of highly flexible production workflows that can respond dynamically to fluctuations in demand or operating conditions (Zhong et al., 2021; Lyons & Lazaroiu, 2020). Empirical studies suggest that IoT implementation leads to measurable improvements in productivity, energy efficiency, and predictive maintenance outcomes in industries as diverse as automotive, pharmaceuticals, and electronics (Vaidya et al., 2018; Said et al., 2021). Complementing IoT is the deployment of Cyber-Physical Systems (CPS), which are deeply integrated frameworks in which computational elements interact directly with physical processes through feedback loops. CPS blends sensors, processors, and actuators within physical manufacturing systems, enabling these systems to monitor conditions, analyse performance, and autonomously execute corrective actions. Such architectures are foundational to the operation of smart factories, as they allow machines and devices to self-organise, coordinate with human operators, and optimise their performance based on real-time environmental data. Notably, CPS technologies extend the capacity for remote control and diagnostics, which became critical during global disruptions such as the COVID-19 pandemic, when physical access to production facilities was restricted (Volker, 2014; Yang & Gu, 2021).

Equally transformative is Digital Twin Technology, which refers to the creation of high-fidelity virtual models of physical systems, synchronised with their real-world counterparts via live data feeds from embedded sensors. Digital twins serve as dynamic simulation environments that allow engineers to test new configurations, predict maintenance needs, and optimise resource allocation without disrupting actual production. In advanced implementations, digital twins also incorporate artificial intelligence algorithms to anticipate system behaviour under varying conditions, thereby enabling prescriptive and even autonomous decision-making (Al-Omari et al., 2023; Belas et al., 2020a). These virtual models have been successfully applied not only in manufacturing but also in logistics, urban infrastructure, and energy grids, reflecting their versatility across domains (Camara, 2024). Artificial Intelligence (AI) and Machine Learning (ML) further expand the intelligence of Industry 4.0 ecosystems by providing tools that autonomously extract patterns and insights from massive, complex datasets. These technologies underpin key Industry 4.0 functionalities such as predictive maintenance, anomaly detection, process optimisation, and quality assurance. AI-powered systems can analyse historical and streaming data to anticipate equipment failures before they occur, thereby reducing unplanned downtime and extending asset lifecycles. Beyond maintenance, cognitive automation driven by AI supports adaptive production planning and inventory management, ensuring that supply chains remain resilient in the face of volatility (Dhamija & Bag, 2020; Eller et al., 2022).

Notably, the integration of AI with IoT and CPS has enabled autonomous manufacturing cells that combine self-organising machines and robots capable of collaborative problem-solving and decision-making (Fialova & Folvarcna, 2020). At the foundation of these capabilities lies Big Data Analytics, which enables the capture, storage, processing, and interpretation of vast volumes of heterogeneous data generated across production systems and supply chains. Big data enables firms to achieve unprecedented levels of operational visibility, traceability, and responsiveness. For instance, advanced analytics tools can detect subtle patterns that indicate emerging bottlenecks or inefficiencies, enabling managers to intervene proactively. Furthermore, big data supports the development of *digital supply chains*, where information flows seamlessly across organisational boundaries, fostering greater collaboration between suppliers, manufacturers, and customers (Gajdosikova et al., 2024; Gavurova et al., 2017). Finally, Cloud Manufacturing leverages cloud computing infrastructure to deliver scalable, on-demand access to computational, storage, and software resources. This model enables geographically dispersed facilities and supply chain partners to collaborate seamlessly, sharing real-time data and coordinating production activities across locations. For small and medium-sized enterprises (SMEs), cloud-based platforms significantly lower the barriers to entry for adopting advanced technologies, offering a cost-effective pathway to digital transformation through pay-as-you-go models. In addition, cloud manufacturing facilitates the integration of edge computing and fog computing, enabling faster data processing at or near the source while maintaining centralised control over enterprise-wide operations (Gray & Kovacova, 2021; Guo et al., 2020). Together, these interdependent technologies form the backbone of Industry 4.0 ecosystems, enabling the transition from rigid, linear production processes to agile, networked, and intelligent manufacturing systems. By bridging the digital and physical worlds, they empower manufacturers to achieve greater operational efficiency, resilience, and customer responsiveness, while laying the groundwork for future paradigms such as Industry 5.0, which emphasises human-centricity and sustainability (European Commission, 2024).

2.3. Impact on global value chains (GVCs)

Industry 4.0 technologies are fundamentally reshaping the architecture and dynamics of Global Value Chains (GVCs), signalling a profound transformation in how production and value creation are organised across borders. Traditionally, GVCs have been characterised by a spatial hierarchy in which high-value-added activities, such as research and development (R&D), design, branding, and marketing, are typically concentrated in advanced economies, while labour-intensive, low-value assembly processes are outsourced to emerging and developing markets (Feng et al., 2009; Hamilton, 2022). Differences in labour costs, infrastructure, and technological capabilities across countries have long underpinned this configuration. However, the diffusion of Industry 4.0 technologies is disrupting this global division of labour by enabling firms to transcend many of the constraints that historically determined the geographic dispersion of production. The integration of advanced digital capabilities, such as automation, additive manufacturing, and cyber-physical systems, into production systems is enabling companies to repatriate manufacturing processes that were previously offshored, a trend commonly referred to as reshoring or back*shoring*. By leveraging highly automated and flexible production technologies, firms in high-cost economies can now offset labour cost differentials and achieve competitive advantages in quality, lead times, and customisation (Hermann et al., 2015; Lamon et al., 2020). Moreover, the strategic deployment of artificial intelligence and real-time analytics facilitates rapid responsiveness to local market needs, making localised production not only technologically feasible but economically advantageous in specific contexts. Recent studies in the European context demonstrate how advanced manufacturing technologies have enabled small and medium-sized enterprises (SMEs) to participate more actively in regional value chains, fostering resilience and reducing dependency on complex, geographically dispersed supply networks (Liao et al., 2017; Marik, 2016).

Beyond production location decisions, Industry 4.0 empowers firms to orchestrate their participation in GVCs with unprecedented agility and precision. Digital supply chains, often conceptualised as *Supply Chain 4.0*, are underpinned by Internet of Things (IoT) sensors, blockchain-enabled ledgers, and advanced analytics that enhance transparency, responsiveness, and risk mitigation across complex networks. These systems provide real-time visibility into material flows, inventory levels, and supplier performance, allowing firms to anticipate disruptions and dynamically reconfigure their operations in response to changing market conditions (Oesterreich & Teuteberg, 2016).; Schwab, 2016). Firms investing in such technologies benefit from enhanced process resilience, lower transaction costs, and improved value retention across the chain, as they can better coordinate production activities, optimise resource utilisation, and strengthen collaboration with partners and customers. Emerging research underscores that digitalisation not only improves operational efficiency but also deepens a firm's integration into GVCs by enabling participation in higher-value segments of the chain. Activities such as design, prototyping, and mass customisation, which were traditionally confined to headquarters in advanced economies, are increasingly distributed across global networks through digital platforms and collaborative tools (Skourdolis et al., 2020; Tang et al., 2022). For instance, additive manufacturing (3D printing) allows for decentralised production close to end markets, while digital twins and virtual reality tools facilitate collaborative design and engineering across geographically dispersed teams (Ukko et al., 2019). These capabilities enable firms to transition from linear, sequential value chains to more dynamic and interactive value networks. As a consequence, GVCs are becoming more knowledge-intensive, less geographically constrained, and increasingly reliant on robust connectivity and advanced data infrastructures (Verhof et al., 2021). This shift reflects a broader structural transformation in which competitive advantage is derived less from cost arbitrage and more from innovation capacity, speed-to-market, and the ability to deliver highly customised solutions. Digitalisation also facilitates the integration of sustainability considerations into GVC governance by enabling better traceability of materials, lifecycle assessments, and compliance with environmental and social standards. Nevertheless, this transformation is not without challenges. The widespread adoption of Industry 4.0 technologies in GVCs raises concerns regarding technological standardisation, data security, and the digital divide between advanced economies and low-income countries. While leading firms in developed economies are capitalising on these technologies to consolidate their positions in GVCs, there is a risk that developing economies could be marginalised if they fail to upgrade their digital infrastructure and workforce capabilities (Vinerean et al., 2022). Consequently, policymakers and industry leaders must address these disparities to ensure that the benefits of digitalisation are equitably distributed across global production networks.

2.4. Smart manufacturing and organisational transformation

Smart manufacturing represents a transformative paradigm in industrial production, characterised by the seamless convergence of automation, artificial intelligence (AI), and cyber-physical infrastructures within factory environments. This integration enables dynamic production reconfiguration, enhanced quality assurance, and mass customisation, allowing firms to respond rapidly to changing customer demands and market fluctuations. At the core of these systems lies the ability to acquire and process real-time data, facilitating machine-to-machine (M2M) communication and the deployment of deep learning algorithms for continuous process optimisation and decision-making (Zabojnik, 2015; Zavadska & Zavadsky, 2020). Smart factories, the physical manifestation of smart manufacturing principles, demonstrate a high degree of digital maturity. They leverage cutting-edge technologies, such as edge computing, which process data closer to the source to reduce latency and enhance responsiveness. Collaborative robots (cobots) work safely alongside human operators, augmenting productivity while handling repetitive or hazardous tasks. Digital twins provide virtual replicas of physical systems, allowing simulation, monitoring, and optimisation across the product lifecycle. Advanced visualisation tools, including augmented reality (AR) and virtual reality (VR), support operators by providing real-time guidance and immersive interfaces for complex assembly or maintenance tasks (Zhou et al., 2023). Sensors and vision-based technologies, such as LiDAR and computer vision, enhance situational awareness, enabling autonomous task execution and precision in complex environments, particularly in high-variability sectors like automotive supply chains (Nagy & Lazaroiu, 2022). Moreover, Industry 4.0 fosters the development of modular and highly flexible production systems that can be rapidly adapted to accommodate new product variants, changes in customer specifications, or fluctuations in production volumes. Predictive modelling and real-time simulation tools enhance the adaptability of manufacturing processes, enabling proactive maintenance strategies and minimising downtime. Augmented reality applications extend these capabilities by facilitating intuitive human-machine interactions, thereby improving worker productivity and operational safety (Zhou et al., 2023). Significantly, smart manufacturing extends beyond technological advancements; it necessitates a holistic rethinking of business models, workforce competencies, and organisational routines. The transition to digitally driven operations requires upskilling employees to handle advanced analytics, robotics, and cybersecurity concerns while fostering cross-disciplinary collaboration and innovation. Organisations must also embrace more agile and data-centric management practices, aligning decision-making structures with the decentralised nature of smart factory systems (Ragazou et al., 2023).

2.5. The Slovak industrial context and Industry 4.0

Slovakia's export-driven economy is highly dependent on its industrial base, with the automotive sector serving as the backbone of the national economy. This sector alone accounts for over 10% of GDP and employs approximately one-tenth of the workforce, underscoring its strategic importance for national growth and social stability (Zabojnik, 2015). As one of the world's leading car producers per capita, Slovakia hosts several major original equipment manufacturers (OEMs), including Volkswagen, Kia, Stellantis (PSA), and Jaguar Land Rover, as well as an extensive network of Tier 1 and Tier 2 suppliers. This dense industrial ecosystem has positioned the country as a crucial node within European and global automotive supply chains. However, despite its impressive production volumes, the domestic share of value added in the automotive industry remains disproportionately low. Much of the intellectual property creation, advanced R&D, and high-value design activities are concentrated abroad, leaving Slovak operations primarily focused on assembly and labour-intensive processes (Pucci et al., 2023). This structural imbalance raises concerns about the country's vulnerability to shifts in global value chains (GVCs), particularly as Industry 4.0 technologies enable manufacturers in high-cost economies to reshore production and move towards more knowledge-intensive activities. National digitalisation strategies, such as the *Digital Transformation Strategy 2030*, recognise the importance of accelerating the uptake of cutting-edge technologies, including artificial intelligence (AI), blockchain, and smart manufacturing systems, to maintain competitiveness. However, these strategic frameworks often lack detailed, sector-specific roadmaps and fail to adequately address the unique challenges faced by small and medium-sized enterprises (SMEs), which form the backbone of the Slovak economy (Ruttimann & Stockli, 2016). Surveys and empirical studies indicate a gradual adoption of Industry 4.0 technologies among Slovak firms; however, progress is uneven due to persistent barriers such as digital infrastructure deficits, skills shortages, and limited access to affordable financing (Savvakis et al., 2020; Schot & Steinmueller, 2018). Nevertheless, Industry 4.0 offers Slovakia a critical window of opportunity to upgrade its position within GVCs. By localising high-value activities such as R&D, prototyping, and digital innovation, the country can transition from being primarily an assembly hub to a centre for advanced manufacturing and innovation. Policy interventions focusing on smart specialisation strategies, talent development programmes, and targeted support for SME digitalisation are essential to avoid marginalisation in future industrial ecosystems and ensure that Slovak firms can actively shape, rather than passively adapt to, the global shift towards smart manufacturing (Sjodin et al., 2018).

2.6. Opportunities and barriers for SMEs

While Industry 4.0 promises significant gains in productivity, flexibility, and competitiveness, its diffusion among SMEs in Slovakia and across Europe is hindered by a set of structural and organisational challenges. Financial constraints remain a primary obstacle, as smaller firms often lack the capital reserves needed for investments in advanced technologies such as automation, IoT, and AI. Compounding these difficulties are shortages of qualified personnel, limited digital literacy among management teams, and uncertainty about the return on investment associated with digital transformation initiatives (Stark, 2016). Organisational inertia, coupled with the absence of clear implementation roadmaps, further exacerbates the digital divide between SMEs and larger enterprises, which typically possess the resources and expertise to lead in Industry 4.0 adoption (Xia et al., 2023). This divide risks entrenching inequalities in productivity and competitiveness within and across national economies. However, Industry 4.0 technologies can also act as an equaliser for SMEs if harnessed effectively. Cloud-based platforms, pay-as-you-go software services, and modular automation solutions offer scalable pathways for smaller firms to develop digital capabilities without incurring prohibitive capital expenditures. For instance, cloud manufacturing enables SMEs to access high-performance computing resources and advanced analytics tools, levelling the technological playing field with larger competitors (Ye et al., 2020). Empirical evidence indicates that SMEs engaging in digital transformation experience notable improvements in supply chain integration, mass customisation capabilities, and market agility, allowing them to respond swiftly to shifting consumer demands (Zhou et al., 2015). To bridge existing gaps, governments, industry associations, and academic institutions must prioritise capacity-building initiatives, foster cross-sectoral partnerships, and simplify access to funding instruments for digitalisation. Awareness-raising campaigns and demonstration projects can play a pivotal role in demystifying Industry 4.0 technologies for SMEs and highlighting their tangible benefits across diverse industrial sectors (DEP, 2024).

2.7. Emerging research directions (2023–2025)

Recent academic and policy discourses emphasise the convergence of Industry 4.0 with broader societal and environmental objectives, reflecting a paradigm shift towards more holistic and inclusive models of industrial development. The European Commission's *Industry 5.0* vision extends beyond efficiency and productivity, integrating sustainability, human-centric innovation, and resilience as core dimensions of future industrial policy (European Commission, 2024). This evolution reframes technological progress as a catalyst for social and environmental well-being rather than merely a driver of economic growth. Industry reports and foresight studies highlight emerging priorities, such as cybersecurity in highly interconnected systems, talent management in digitally transformed workplaces, green manufacturing practices aligned with climate goals, and the integration of generative AI into production planning and design processes (Saona et al., 2019). Furthermore, successful digital transformation increasingly depends on the development of unified data architectures, proactive worker engagement strategies, and secure-by-design frameworks to protect against cyber vulnerabilities (Ribeiro-Navarrete et al., 2019). Overall, the contemporary trajectory of Industry 4.0 is shaped not only by technological maturity but also by organisational readiness, workforce capability, and supportive regulatory ecosystems. For Slovakia and other export-oriented economies, the strategic deployment of Industry 4.0 technologies will be decisive in determining their long-term relevance and resilience within globally distributed production networks. Without deliberate investments in digital infrastructure and skills, these countries risk being relegated to peripheral roles in emerging digital value chains.

3. Materials and methods

To achieve a cohesive and methodologically robust synthesis of the three thematic domains, automotive technologies, export network dynamics, and SME technological readiness, we adopted a deeply integrative secondary data analysis framework. This strategy was designed to unify and triangulate diverse streams of quantitative and qualitative evidence drawn from a wide array of primary studies, reports, and databases, thereby ensuring both breadth and depth in the analytical process. Beyond mere aggregation, the approach deepened analysis through the application of innovative visualisation techniques, including comparative mapping, heatmaps, and trend projections, as well as comprehensive narrative synthesis to capture nuanced relationships across datasets. The framework was anchored in a rigorous analytic design that consolidated multiple data sources, ranging from macroeconomic indicators and industry-specific performance metrics to firm-level case studies and survey data, into an integrated structure. Advanced graphical and statistical tools, such as multidimensional scaling, cluster analysis, and time-series visualisation, were employed to identify patterns, interdependencies, and emergent themes within and across the thematic domains. This enabled the derivation of strategic insights tailored to Slovakia's Industry 4.0 transformation, with particular emphasis on assessing potential pathways to enhance competitiveness and value creation in global value chains. Our methodological foundation followed a multi-layered process that unfolded in structured steps. Initially, a systematic scoping of relevant literature and datasets was conducted to map the existing knowledge landscape and identify analytical gaps. This was followed by data harmonisation and normalisation procedures to ensure comparability across diverse sources. In the subsequent phase, exploratory and confirmatory analyses were carried out to test thematic linkages, supported by visual and statistical representations that enriched interpretative validity. The final phase synthesised these insights into a coherent framework for understanding the interplay between technological adoption, network integration, and SME readiness in Slovakia's evolving industrial ecosystem:

Step 1: Data Collection

- Trade data were sourced from Eurostat and the Slovak Statistical Office, including exports broken down by country of destination and product classification (with a focus on HS 8703 and HS 8708 for motor cars and automotive parts).
- OECD's Trade in Value Added (TiVA) datasets provided insight into Slovakia's domestic content in exports relative to peer countries.
- Foreign direct investment (FDI) records were obtained from SARIO's annual reports, which highlight sectoral FDI inflows, origin countries, and project typologies.
- Corporate data from PSA Group Slovakia, including production volumes, supply chain structures, and levels of automation, were pivotal for framing the automotive case study.
- A prior questionnaire of industry employees (covering four companies and ~20 respondents) was incorporated to assess perceptions of Industry 4.0 readiness, barriers to digitalisation, and enablers of technological adoption.

Step 2: Data Preprocessing and Integration

- Collected datasets were cleaned, standardised, and merged to form a unified analytical base, ensuring consistency and accuracy across all data sources.

Step 3: Graphical and Statistical Analysis

- Original figures and tables from the three manuscripts were refined for clarity and consistency.
- New visualisations were created, including:
  - Comparative bar charts of Export-to-GDP ratios by country.
  - Sectoral FDI stock shares and FDI sources by country.
  - Scatterplots mapping the top car-exporting markets against importer GDP per capita to reveal nuanced trade patterns.
  - Charts were annotated to emphasise Slovakia's positioning (highlighted in blue) relative to regional peers (shown in grey tones).

Step 4: Thematic Coding and Synthesis

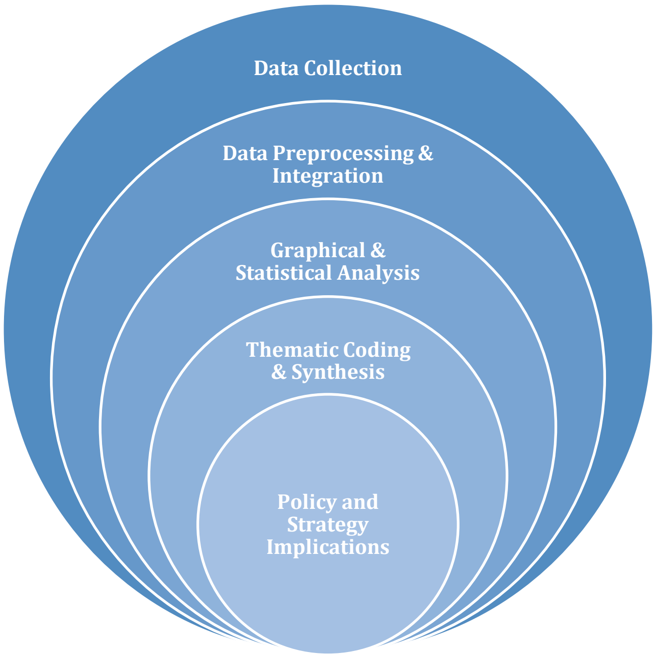
- Qualitative insights were coded to identify recurring patterns, such as:
  - Strengths: Advanced manufacturing infrastructure in automotive multinationals.
  - Weaknesses: Low domestic R&D intensity and skills shortages.
  - Opportunities: EU digitalisation funding programmes and potential Industry 4.0 regional clusters.
  - Threats: Dependence on foreign OEMs and risks of technological lock-in.

Step 5: Policy and Strategy Implications

- Insights from quantitative and qualitative streams converged to inform strategic recommendations tailored to Slovakia's industrial context.

The workflow diagram below visualises the overall process from data acquisition to synthesis and implications (Figure 1):

Figure 1: Workflow diagram



Source: Author's compilation

4. Results

4.1. Export performance and value-added

Slovakia's economic structure reflects a pronounced export orientation, a characteristic it shares with several advanced European economies. This export dependency underscores the country's integration into global trade networks and its reliance on external markets for sustained economic growth. Table 1 compares the world's largest economies by exports and GDP, revealing substantial disparities in export reliance. For instance, Germany's export-to-GDP ratio is 39.1%, vastly exceeding the United States' 9.4%, highlighting Germany's deep-rooted trade integration and focus on high-value manufacturing industries. This contrast reflects fundamentally different economic models: while the United States relies more on its large domestic market, Germany's growth strategy is closely tied to its role as a global exporter of advanced industrial goods, particularly in the automotive and machinery sectors.

In this context, Slovakia, with its smaller economy, emerges as an outlier. Despite its size, the country maintains an export ratio comparable to Germany's, signalling a highly trade-oriented growth model that is heavily skewed toward automotive production. This reliance, however, also makes Slovakia more vulnerable to fluctuations in global demand and supply chain disruptions, underscoring the importance of enhancing its domestic value-added capacity and technological upgrading to secure its long-term competitiveness.

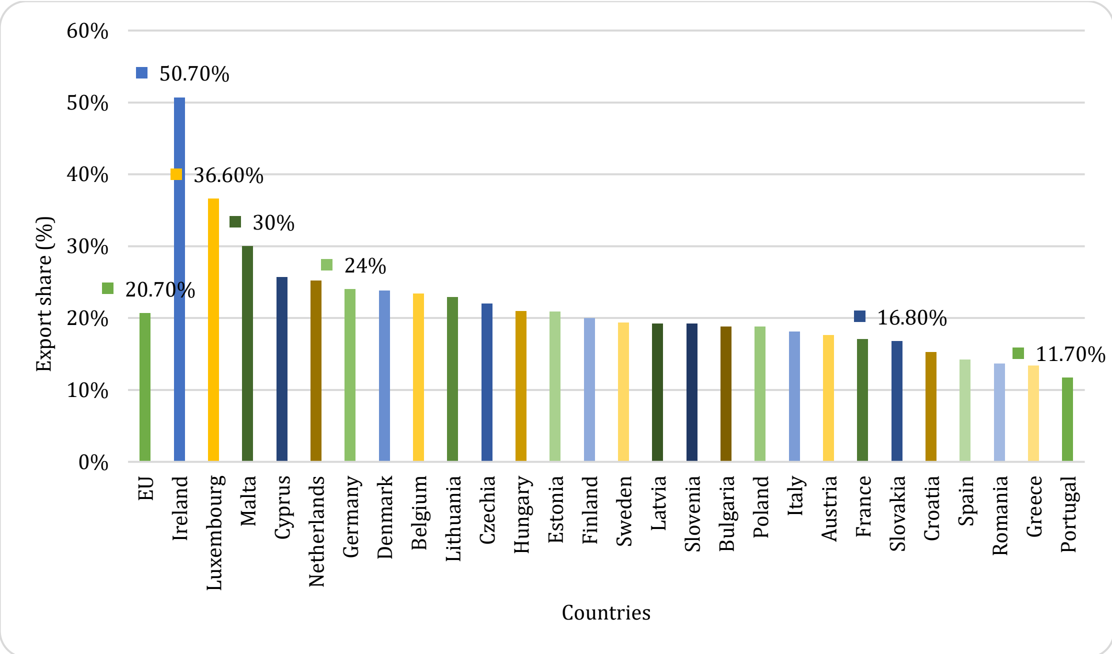
Although Slovakia does not appear in Table 1 due to its smaller GDP, the country's export intensity is strikingly similar to Germany's, with an export ratio of approximately 40%, signalling its heavy dependence on foreign trade, particularly within the automotive industry. This relationship is visualised in Figure 2, which shows how Slovakia aligns with high-performing export economies despite its smaller size.

Table 1: Export performance of companies from the largest economies in 2019 (%)

Order (GDP)			State	GDP (bl-US)	Export (bl-US)		Export together	Export per.
					Goods	Services		
2020	2019	2014	World together	84,538	17,583	4,914	22,497	26.6%
1	1	1	USA	22,675	1,431	705	2,136	9.4%
2	2	2	China	16,642	2,590	280	2,870	17.2%
3	3	3	Japan	5,378	640	160	800	14.9%
4	4	4	Germany	4,319	1,377	311	1,688	39.1%
5	6	10	GB	3,124	399	342	741	23.7%
6	5	6	India	3,049	275	203	478	15.7%
7	7	5	FR	2,938	475	246	721	24.5%
8	8	9	Italy	2,106	496	87	583	27.7%
9	10	7	Canada	1,883	390	86	476	253%
10	12	11	South Korea	1,807	513	87	600	33.2%
11	11	8	Russia	1,711	337	47	384	22.4%
12	9	12	Brazil	1,492	209	28	237	15.9%

Source: Author's compilation.

Figure 2: **Export share of GDP for major economies in 2019**



Source: Author's compilation

Germany's position as both a technological powerhouse and a leading export destination for Slovak goods underscores Slovakia's structural reliance on external markets and foreign demand for its industrial base. With over 60% of Slovak automotive exports destined for Germany, Slovak suppliers are deeply embedded within Germany's global value chains (GVCs), effectively functioning as critical nodes in the supply networks of major German original equipment manufacturers (OEMs) such as Volkswagen, BMW, and Daimler. This integration, while offering opportunities for scale and access to premium markets, also exposes Slovakia to the technological and regulatory demands arising from initiatives like Industrie 4.0, as well as strategic investments such as Tesla's European Gigafactory, which are reshaping production paradigms across Europe. Further insights into Slovakia's position in GVCs emerge from an analysis of domestic value-added contributions to exports. As shown in Figure 2, Slovakia ranks 22nd among EU member states, with only 16.8% of export value added originating domestically. This means that more than 80% of the value embedded in its exports is derived from foreign inputs, a striking contrast to economies such as Ireland (~51%) and Germany (24%), which retain significantly larger proportions of value domestically. These disparities reflect the asymmetrical distribution of knowledge-intensive and high-margin activities within the GVC hierarchy, in which Slovakia remains largely confined to labour-intensive assembly and low-complexity manufacturing. This structural composition underscores the urgent need for Slovakia to evolve beyond its predominantly assembly-focused industrial model. Transitioning to a higher rung of the GVC ladder will require integrating advanced functions, such as research and development (R&D), electronics engineering, software development, and system-level innovation, into domestic production ecosystems. In this regard, the adoption of advanced manufacturing technologies, including digital twins, predictive analytics, robotics, and artificial intelligence, presents a critical pathway for Slovakia to enhance its technological sovereignty and capture a greater share of the value created within its export industries. Such a transformation would not only increase domestic value retention but also strengthen Slovakia's industrial base's resilience against external shocks, including supply chain disruptions and shifts in global trade patterns.

4.2. Foreign investment and industrial structure

Foreign Direct Investment (FDI) patterns further illuminate Slovakia's structural positioning within global production networks (Table 2).

Table 2: Export performance of companies from the largest economies in 2019 (%)

FDI STOCK IN SVK			
SECTOR	**%**	**TERRITORY**	**%**
Automotive industry, including subcontractors	30%	Germany	19%
Electrical industry, including subcontractors	13%	South Korea	10%
Engineering industry	11%	USA	7%
Chemical industry, plastics processing and pharmacy	8%	Austria	7%
Metalworking industry and metal surface treatment	7%	Slovakia	6%
Business service centres	5%	Italy	5%
Information and communication technologies	5%	Denmark	5%
Wood and paper industry	4%	France	4%
Other services	3%	UK	4%
Textile, leather and clothing industry	3%	Belgium	4%
Logistics and transport services	2%	Czechia	4%
Furniture and sanitary industry	2%	Switzerland	3%
Building industry	2%	Spain	3%
Research & Development	2%	Netherlands/ Japan	3%
Others	3%	China	1%
		Others	12%

Source: Author's compilation.

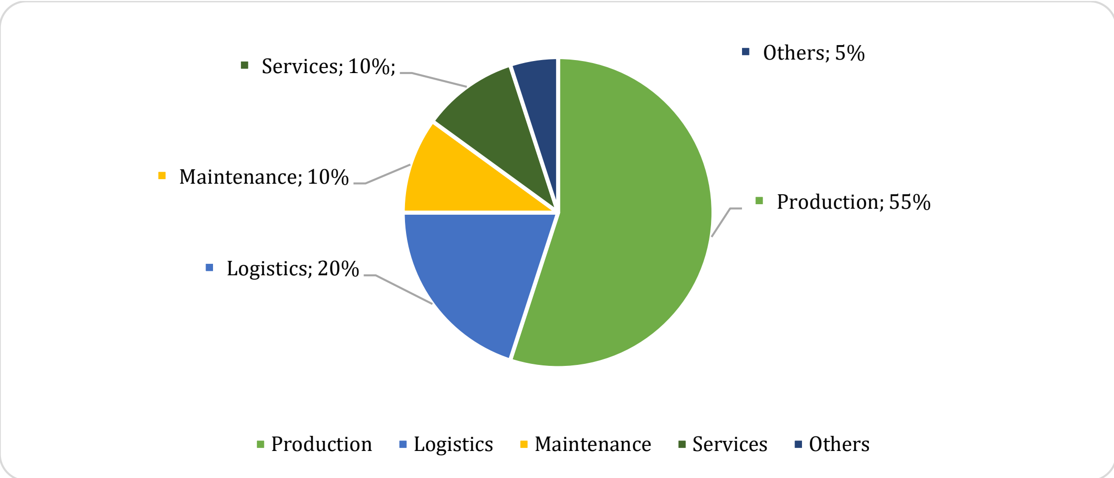
Table 2 reveals that the automotive industry, including vehicle assembly and parts manufacturing, accounts for a striking 30% of Slovakia's cumulative foreign direct investment (FDI) stock, positioning it as the largest recipient sector by a considerable margin. This dominance reflects Slovakia's emergence as a key European automotive assembly hub over the past two decades. Electronics and engineering follow with a combined share of 24%, underlining their supporting role in Slovakia's industrial landscape. By contrast, high-value sectors such as research and development (R&D) services and information and communication technologies (ICT) remain significantly underrepresented, attracting only 2–5% of total FDI. This asymmetry indicates a structural bias in foreign investment toward production-oriented activities rather than innovation-intensive domains.

The distribution of foreign investment by country further highlights Slovakia's reliance on a narrow group of industrial powerhouses. Germany leads with 19% of the total FDI stock, driven primarily by Volkswagen's substantial investments in its Bratislava plant and related supply networks. South Korea accounts for 10%, reflecting Kia's significant presence in Žilina, which has catalysed the development of local supplier ecosystems. Other notable contributors include the United States (7%) and Austria (7%), while Western European countries such as Italy, Denmark, and France collectively contribute approximately 20%. Strikingly, high-R&D-intensive economies like Japan and the Netherlands make relatively modest contributions, each accounting for only 3% of Slovakia's total FDI stock. These patterns carry important strategic implications. Slovakia's heavy reliance on German and South Korean investments effectively aligns its industrial standards, supply chain practices, and technological networks with the trajectories of these economies. Initiatives such as Germany's Industrie 4.0 strategy and South Korea's Smart Factory programmes exert a substantial influence over Slovak suppliers, compelling them to adopt advanced manufacturing practices and upgrade their technological capabilities in line with these global leaders' standards. While this integration offers pathways for technological diffusion and quality improvement, it also underscores a structural dependency that limits Slovakia's autonomy in setting its own innovation agenda. The relative paucity of FDI in R&D-intensive sectors reinforces earlier findings regarding Slovakia's limited domestic research capacity. This imbalance highlights the risk that the country will remain a downstream node in global value chains, confined primarily to labour-intensive assembly and low-complexity manufacturing tasks. To overcome this constraint, Slovakia must actively cultivate its own "innovation identity" by fostering environments conducive to technological co-creation and encouraging higher-value-added activities such as R&D, product design, and software development. Strengthening these capabilities is critical to transitioning from a peripheral assembly hub to a strategic partner in global innovation ecosystems.

4.3. Industry 4.0 deployment in automotive production

Building on macroeconomic trends, firm-level analyses provide insights into how Industry 4.0 technologies are deployed across Slovakia's leading manufacturing plants. At the PSA Group Slovakia facility in Trnava, which produces the Citroën C3 and Peugeot 208 models, automation and digitalisation initiatives are particularly illustrative.

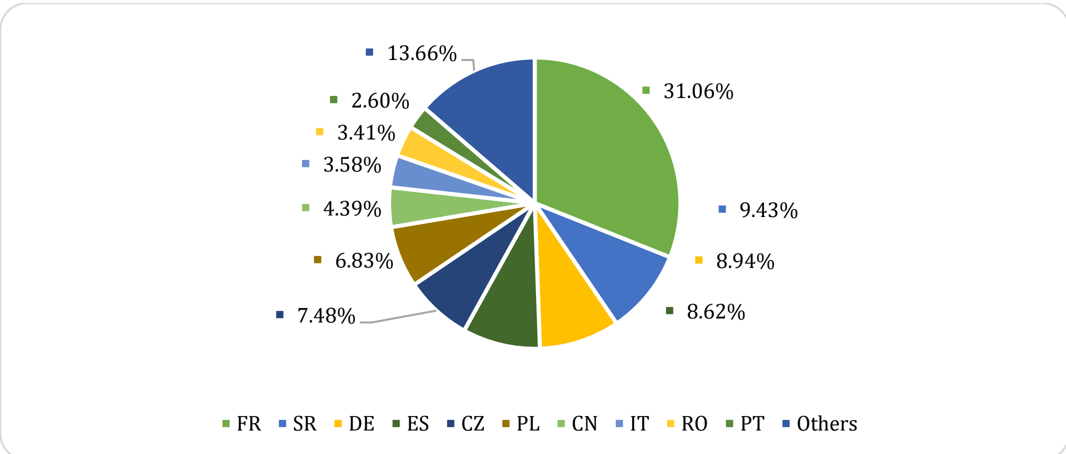
Figure 3: PSA Group SVK automation areas



Source: Author's compilation

Figure 3 shows that 55% of the plant's industrial tasks are already automated. Robotics dominates core manufacturing processes, including welding and painting, accounting for 85% of automated tasks. Remaining functions, such as logistics (20%) and maintenance (10%), highlight the increasing importance of smart connectivity between equipment and software in supporting factory operations. Value-added projections further highlight the transformative potential of advanced manufacturing systems. In 2020–2021, Slovakia's share of value added to the C3/208 vehicles was approximately 9.5%, while France accounted for 31.1%. However, Figure 4 models a scenario in which full Industry 4.0 integration at PSA, including predictive analytics, cognitive automation, and IoT-enabled processes, raises Slovakia's contribution to ~20% by 2023.

Figure 4: Percentage of value-added for C3 and 208 vehicles by country (2020–2021)



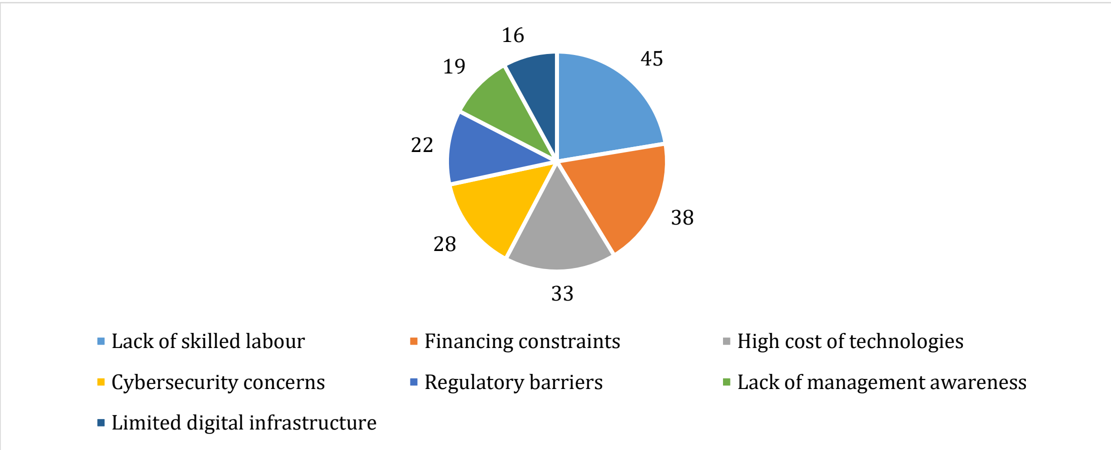
Source: Author's compilation

4.4. SME technology adoption and barriers

While large firms across Europe have made significant strides in digitalisation and the deployment of Industry 4.0 technologies, small and medium-sized enterprises (SMEs) continue to face substantial structural and operational barriers that hinder their ability to keep pace with technological transformation. These firms, which constitute the backbone of Slovakia's economy, are particularly vulnerable to the challenges of the digital transition due to their limited financial and human resources. Figure 5, adapted from an EU-wide survey, highlights the most critical obstacles reported by SMEs on their path toward digitalisation. Foremost among these is a shortage of skilled labour, reflecting a pervasive lack of employees with the necessary competencies in areas such as data analytics, robotics, and cybersecurity. This skills gap severely constrains SMEs' ability to plan, implement, and operate advanced technological systems. Secondly, difficulties in accessing financing remain a significant impediment, as the capital-intensive nature of Industry 4.0 investments, covering areas such as automation, cloud infrastructure, and IoT devices, poses a prohibitive risk for smaller firms with tight cash flows.

Furthermore, many SMEs cite uncertainty regarding returns on investment in digital technologies, which fuels organisational inertia and risk aversion. These barriers are compounded by additional factors, including limited management awareness of digital opportunities, high technology acquisition costs, and the complexity of navigating regulatory frameworks for data protection and cybersecurity. As a result, SMEs often lag behind their larger counterparts in adopting even basic digital tools, deepening the digital divide and potentially excluding them from future value creation in global supply chains. However, there is growing recognition that targeted interventions, such as subsidised training programmes, simplified financing instruments, and collaborative platforms for knowledge sharing, can mitigate these barriers. By leveraging cloud-based solutions and modular automation systems, SMEs could overcome scale disadvantages and participate more effectively in digitalised production ecosystems.

Figure 5: Percentage of SMEs Reporting (%)



Source: Author's compilation

Despite these challenges, a growing number of Slovak SMEs are experimenting with innovative technological solutions, illustrating the transformative potential of Industry 4.0 when coupled with targeted support mechanisms. For instance, some firms have successfully piloted sensor-linked machinery for predictive maintenance, enabling them to anticipate equipment failures and reduce costly downtime. Others have adopted virtual reality (VR) training simulations to rapidly upskill workers in complex production environments, thereby bridging gaps in technical competencies without interrupting workflows. These pioneering cases, though still limited in scale, provide compelling evidence that even resource-constrained enterprises can harness advanced technologies to enhance operational efficiency and competitiveness. These initiatives underscore the critical role of financial and institutional support in facilitating SME digital transformation. Access to subsidised loans, EU structural funds, and government-led digitalisation grants can significantly lower the barriers to entry for high-cost technologies such as automation, robotics, and cloud computing. Moreover, non-financial support, such as mentoring programmes, digital literacy campaigns, and regulatory simplification, further empowers SMEs to navigate the complexity of digital ecosystems. An auspicious development in this context is the rise of collaborative platforms and "Industry 4.0 consortia." These networks enable SMEs to pool resources, share expertise, and co-develop digital solutions in partnership with research institutes, larger enterprises, and technology providers. Such models mitigate the disadvantages of scale and provide access to shared infrastructure, such as testbeds, simulation environments, and technical support services. By fostering collective innovation, consortia create an inclusive environment where SMEs can meaningfully participate in digital value chains rather than remain peripheral players. As Durana et al. (2021) note, these collaborative frameworks could become critical enablers for democratising access to Industry 4.0 technologies, ensuring that the benefits of digitalisation extend beyond large multinational corporations to the broader SME sector.

5. Discussion

The findings of this study underscore the transformative potential of Industry 4.0 technologies in redefining Slovakia's industrial competitiveness and strategic positioning within global value chains (GVCs). Advanced sensing technologies, artificial intelligence (AI), and networked infrastructure are emerging as critical enablers of higher-value capture, particularly in the automotive sector. The deployment of computer vision algorithms, remote sensing data fusion, and cyber-physical systems (CPS) has already enabled measurable improvements in process monitoring, quality assurance, and supply chain integration, as demonstrated in PSA Group Slovakia's operations for Citroën C3 and Peugeot 208 models (Juracka et al., 2024). However, despite these advancements, the country's domestic R&D ecosystem remains underdeveloped, limiting the capacity for endogenous innovation and constraining Slovakia's ability to transition from a peripheral assembly hub to a co-creator of advanced industrial technologies (Valaskova et al., 2022). The synthesis of export and foreign direct investment (FDI) data further illuminates a structural dependency on foreign OEMs and high-capital economies such as Germany and South Korea. These countries' technological trajectories, driven by initiatives such as Germany's *Industrie 4.0 and South Korea's Smart Factory strategies, exert a powerful influence on* Slovak suppliers (Nica, 2021). On the one hand, this alignment facilitates technology transfer and creates pathways for upgrading production standards. On the other hand, it exposes Slovakia to external vulnerabilities, as strategic shifts in these leading economies or disruptions in their supply chains could have disproportionate effects on Slovakia's industrial base. Moreover, Slovakia's moderate ranking in the Digital Economy and Society Index (DESI) highlights gaps in critical enabling infrastructures such as IoT networks and high-speed connectivity, which are preconditions for scaling up smart manufacturing ecosystems (Pavlinek & Zenka, 2016).

A key insight emerging from this study is that while large multinational enterprises have made notable strides in adopting Industry 4.0 technologies, small and medium-sized enterprises (SMEs), the backbone of the Slovak economy, face significant structural and organisational barriers that hinder their participation in the digital transformation. Financial constraints limited managerial awareness, and a shortage of skilled personnel consistently emerged as a critical impediment across multiple studies (Pisar & Bilkova, 2019; Popescu et al., 2022). Interestingly, qualitative data suggest that the lack of workforce skills is an even more pressing concern than access to financing, as SMEs struggle to recruit and retain employees with competencies in advanced analytics, robotics, and cybersecurity (Potocan et al., 2021). These skills gaps limit SMEs' ability to conceptualise, implement, and maintain complex digital systems, perpetuating a digital divide that risks excluding them from high-value segments of GVCs. Nonetheless, the evidence also points to promising developments that demonstrate the transformative potential of Industry 4.0 when coupled with appropriate support mechanisms. Some Slovak SMEs have successfully piloted sensor-linked machinery for predictive maintenance, which enables them to anticipate equipment failures and reduce unplanned downtime. Others have implemented virtual reality (VR) training simulations to rapidly upskill workers, bridging technical competence gaps without disrupting production workflows (Rossini et al., 2019). These pioneering cases illustrate that, with targeted financial and institutional support, SMEs can overcome scale disadvantages and leverage digital technologies to enhance competitiveness. Collaborative frameworks, such as *Industry 4.0 consortia* and public–private innovation platforms, emerge as particularly effective models for pooling resources, sharing expertise, and democratising access to advanced technologies (Rußmann et al., 2015). At a systemic level, the findings highlight a pressing need for Slovakia to embed higher-value functions, such as R&D, electronics engineering, and software development, into its industrial fabric. Currently, over 80% of the value embedded in Slovakia's exports is derived from foreign inputs, a stark contrast to countries such as Ireland (~51%) and Germany (24%), which retain significantly larger shares of domestic value added (Valaskova et al., 2022). This asymmetry underscores the importance of moving beyond labour-intensive assembly toward more knowledge-intensive, innovation-driven activities. Advanced manufacturing technologies, including digital twins, AI-driven predictive analytics, and robotics, could serve as catalysts for this transition, but their successful integration requires coordinated investments in human capital, organisational transformation, and supporting policy frameworks (Samadhiya et al., 2023; Dalenogare et al., 2023). Moreover, the convergence of Industry 4.0 with the European Commission's Industry 5.0 vision suggests that future industrial policies must incorporate sustainability, resilience, and human-centric innovation as core dimensions (European Commission, 2024). This expanded paradigm reframes technological progress as a means not only to achieve efficiency and competitiveness but also to promote inclusive and sustainable industrial ecosystems. For Slovakia, aligning with this vision would entail fostering multi-stakeholder collaborations that bring together large OEMs, SMEs, research institutions, and policymakers to co-create solutions that balance economic, social, and environmental objectives.

From a policy perspective, the findings point to several strategic imperatives: (1) strengthening digital infrastructure and ensuring nationwide access to high-speed connectivity; (2) implementing large-scale upskilling and reskilling programmes to address workforce shortages in digital competencies; (3) developing financial instruments tailored to SME needs, such as innovation vouchers and risk-sharing mechanisms; and (4) incentivising collaborative innovation networks and regional Industry 4.0 hubs. Without such interventions, there is a risk that Slovakia will remain locked into low-margin, assembly-focused roles within global production networks, unable to fully capitalise on the opportunities presented by the Fourth Industrial Revolution (Datta et al., 2013; Durana & Valaskova, 2022). In sum, this integrative analysis provides a holistic framework for understanding how Industry 4.0 technologies and supporting infrastructures can collectively reshape Slovakia's industrial landscape. By synthesising insights from automotive value chains, export dynamics, and SME adoption challenges, this study highlights both the opportunities and bottlenecks in Slovakia's digital transformation journey. The road ahead will require not only technological readiness but also organisational agility, policy coherence, and societal commitment to ensure that Industry 4.0 becomes a driver of sustainable, inclusive, and resilient growth.

6. Conclusion

This study has presented a comprehensive and integrative analysis of Slovakia's Industry 4.0 journey, weaving together the interconnected domains of advanced sensing and vision technologies in the automotive sector, the role of cyber-physical networks in strengthening export competitiveness, and the transformative potential of artificial intelligence and robotics for small and medium-sized enterprises. By uniting these previously disparate strands of research, the article provides a nuanced understanding of how digital innovations are reshaping Slovakia's industrial landscape and identifies critical pathways to ensure these technologies contribute to sustainable and inclusive economic growth. In the automotive sector, Slovak manufacturers have increasingly embraced cutting-edge technologies such as computer vision, remote sensing, and Internet of Things platforms to create smart factory environments. These innovations enable real-time process monitoring, predictive maintenance, and autonomous decision-making, laying the foundation for a more adaptive and efficient production system.

The findings reveal that these technological upgrades hold the potential to significantly enhance Slovakia's domestic value-added contribution, as demonstrated by projected increases in the local content of key vehicle models. By integrating intelligent manufacturing systems into production processes, Slovakia can move beyond its traditional focus on assembly operations and begin to anchor higher-value activities such as design, prototyping, and software engineering within its borders. This shift is essential for mitigating vulnerabilities arising from overreliance on external markets and for securing a more resilient industrial base capable of withstanding global supply chain disruptions and technological shifts. At the global trade and export level, the deployment of cyber-physical systems and advanced wireless networks is reinforcing Slovakia's competitiveness within global value chains. However, the analysis underscores that the country remains structurally dependent on technologically advanced economies, particularly in terms of knowledge-intensive activities and innovation leadership. The concentration of foreign direct investment in production-oriented sectors, combined with the under-representation of research and development-intensive industries, highlights a critical gap that must be addressed if Slovakia is to climb the global value chain ladder. Moving from an assembly-focused industrial model to one characterised by high levels of innovation and digital sophistication will require deliberate investments in technological infrastructure, workforce development, and the creation of collaborative ecosystems that foster innovation and knowledge exchange. For small and medium-sized enterprises, Industry 4.0 presents both opportunities and formidable challenges. While large multinational corporations often have the financial and organisational resources to implement advanced digital technologies, many SMEs remain constrained by financial limitations, skills shortages, and uncertainty regarding the returns on investment in digital transformation initiatives. These barriers perpetuate a digital divide that risks excluding SMEs from future sources of value creation. Nevertheless, there are emerging examples of Slovak SMEs that have successfully piloted sensor-integrated machinery for predictive maintenance and adopted virtual reality simulations for workforce upskilling. These pioneering initiatives demonstrate that, with appropriate institutional and financial support, smaller firms can harness advanced technologies to enhance their operational efficiency and competitiveness. Collaborative platforms and industry consortia offer promising mechanisms for mitigating scale disadvantages, enabling SMEs to pool resources, share expertise, and co-develop solutions in partnership with research institutions and larger enterprises. The findings of this study highlight the importance of a coordinated, multidimensional approach to digital transformation.

Strategic investments in research and development ecosystems and in expanding Slovakia's capacity for technological innovation are essential to creating the conditions for Industry 4.0 to flourish. Scaling up digital infrastructure, including nationwide 5G and IoT connectivity, will provide the backbone for advanced manufacturing systems and enable seamless integration into global digital trade networks. Equally critical is the strengthening of skill pipelines through enhanced STEM education, vocational training programs, and lifelong learning initiatives focused on digital competencies, robotics, and systems engineering. These efforts must be complemented by measures to increase managerial awareness of Industry 4.0 technologies and their transformative potential, fostering a cultural shift towards innovation and continuous improvement across all levels of industry.

This article contributes to the literature by presenting an original, holistic framework for understanding Industry 4.0 in the Slovak context. The analysis bridges macroeconomic trends, firm-level data, and policy insights to offer a roadmap for transitioning from traditional manufacturing paradigms to intelligent, networked, and innovation-driven production systems. By elucidating the synergies between transport-focused technologies, connected manufacturing networks, and organisational strategies for SME transformation, the study provides actionable recommendations for policymakers and business leaders alike. Slovakia now finds itself at a critical juncture in its industrial development. The choice lies between continuing with a model of low value-added production, which leaves the country vulnerable to external shocks and technological dependency, or embracing the transformative potential of Industry 4.0 to catalyse sustainable growth and secure a more prominent role in global value chains. While the path forward is fraught with challenges, it is also filled with unprecedented opportunities. With strategic investments, an inclusive innovation strategy, and a commitment to fostering collaboration across firms and sectors, Slovakia has the capacity to mobilise Industry 4.0 technologies and reposition itself as a dynamic and resilient player in the global industrial ecosystem.

Conflicts of interest

The author declares no conflict of interest.

Citation information

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