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INNOVATIVE STRATEGIES FOR SUSTAINABLE GROWTH IN THE DIGITAL ECONOMY

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Abstract: This paper examines the role of innovative strategies in fostering sustainable growth within the digital economy, with a specific focus on small and medium enterprises (SMEs). Employing a Systematic Literature Review (SLR) methodology, the study highlights the interplay between digital transformation, innovation, and sustainability. Key findings emphasize the importance of integrating digital technologies and green practices to ensure long-term competitiveness. This research presents actionable insights supported by visual analyses, enhancing the understanding of innovation strategy development in the context of evolving market dynamics.

Keywords: innovation strategy, digital transformation, green innovation, business model, sustainability, SMEs, SALSA methodology

Introduction

In the modern global economy, small and medium enterprises are pivotal in driving innovation, employment, and economic stability. However, their sustainability and competitive advantage increasingly depend on their ability to innovate and adapt to digital transformations. The integration of digital technologies, coupled with innovation strategies, has proven to be essential in enabling SMEs to overcome resource constraints and thrive in competitive markets.

The digital economy has fundamentally reshaped the way businesses operate, interact with customers, and achieve growth. For SMEs, digital transformation offers new opportunities, such as improving operational efficiency, accessing global markets, and adopting sustainable practices. Nevertheless, it also presents challenges, including high implementation costs, a lack of expertise, and resistance to change.

This paper aims to explore innovative strategies that facilitate sustainable growth for SMEs within this evolving landscape. By examining the interplay between digital transformation, green innovation, and sustainable practices, the study provides actionable insights for policymakers, entrepreneurs, and industry stakeholders.

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Innovation Strategies and Sustainable Growth

Innovation strategies are critical tools for businesses seeking to maintain relevance and competitive advantage in dynamic markets. These strategies encompass various dimensions, including product innovation, process improvements, and business model transformations, each serving distinct yet interconnected purposes. There are:

- **product innovation:** involves the development of new or significantly improved goods and services that meet changing customer needs or open new market opportunities. For example, companies introducing energy-efficient appliances not only cater to consumer demand but also align with sustainability goals,
- **process innovation:** refers to the optimization of operational processes to enhance efficiency, reduce costs, and minimize environmental impact. Lean manufacturing techniques or automation in production exemplify such innovations,
- **business model innovation:** focuses on reimagining how a company creates, delivers, and captures value. Successful examples include subscription-based models like Netflix, which have transformed traditional industries. [1,2]

The Resource-Based View (RBV) theory highlights the importance of leveraging unique, inimitable resources, such as proprietary technology, skilled personnel, or strong network, as a foundation for sustained competitive advantage. Meanwhile, the dynamic capabilities framework emphasizes the ability of firms to adapt, integrate, and reconfigure internal and external competencies in response to environmental changes. [3]

For SMEs, innovation strategies offer a pathway to overcome resource limitations by fostering agility, enabling them to compete with larger firms. By embedding sustainability within these strategies, SMEs can achieve not only economic gains but also societal and environmental benefits, securing long-term growth. [3,4]

Digital Transformation as a Catalyst

Digital transformation has emerged as a game-changer in modern business, enabling organizations to integrate advanced technologies across operations, enhance decision-making, and unlock new value streams. For SMEs, digitalization serves as a powerful catalyst for innovation and competitiveness. Belong here:

- **efficiency gains:** digital tools such as cloud computing, automation, and IoT (Internet of Things) streamline processes, reduce waste, and improve productivity. For example, automated inventory systems optimize stock levels, reducing costs and enhancing customer satisfaction,
- **market agility:** digital platforms enable SMEs to respond quickly to market changes by providing real-time data insights. E-commerce and social media channels, for instance, allow businesses to tap into global markets with minimal upfront investment,
- **facilitation of green innovation:** digital transformation supports sustainability efforts by enabling the monitoring of environmental performance, adoption of energy-efficient technologies, and implementation of circular economy principles. For example, blockchain can track supply chains, ensuring ethical sourcing and reduced waste. [3,5,6]

Companies that adopt digital tools report not only increased efficiency but also improved environmental stewardship. For example, firms leveraging AI-driven analytics can optimize energy consumption in manufacturing, contributing to both cost savings and reduced emissions. However, while digital transformation offers immense potential, it also presents challenges. SMEs often struggle with limited access to technology, lack of digital literacy, and high initial investment costs.

Addressing these barriers through policy support, training programs, and financial incentives is essential to ensure that digital transformation benefits are widely accessible. [5,6]

By serving as a catalyst, digital transformation accelerates innovation, drives sustainable practices, and equips SMEs to compete in a globalized economy characterized by rapid technological and environmental shifts. [7]

Objectives

In an era marked by rapid technological advancements and heightened sustainability demands, SMEs face unique challenges and opportunities. This research aims to address these dynamics by defining clear objectives that guide the exploration of innovative strategies in the digital economy. The outlined objectives serve as a framework to analyze how SMEs can leverage digital transformation and green innovation to achieve sustainable growth and competitive advantage.

The research is motivated by three key questions:

- How can SMEs leverage innovation to sustain growth in the digital economy?
- What are the barriers to implementing digital and green innovation strategies?
- How can innovation strategies be aligned with sustainability goals to create a long-term competitive advantage?

By focusing on the intersection of innovation, sustainability, and digitalization, the objectives aim to uncover actionable insights for SMEs to navigate market complexities, overcome barriers, and align their practices with long-term global trends. These goals are not only theoretical but also practical, offering pathways for real-world application to ensure resilience and adaptability in a fast-evolving economic landscape.

Methodology

This study employs a Systematic Literature Review (SLR) methodology structured according to the SALSA (Search, Appraisal, Synthesis, and Analysis) framework. The SALSA approach ensures methodological rigor, minimizes bias, and enhances reproducibility by systematically identifying, evaluating, and synthesizing relevant literature. The SALSA methodology includes the following steps. [7,8]

1. **Search**

The search process involved identifying peer-reviewed articles, case studies, and industry reports from trusted academic databases, including Scopus, Web of Science, and Google Scholar. Keywords such as “innovation strategy,” “digital transformation,” “green innovation,” and “sustainable business growth” were utilized. Inclusion criteria emphasized contemporary relevance (2015–2024), methodological rigor, and alignment with the research objectives. [3,9]

- **Objective alignment:** this step directly supports the first objective, providing a comprehensive pool of insights into the interplay between innovation, sustainability, and digital transformation.

2. **Appraisal**

The appraisal stage involved a critical evaluation of 75 shortlisted studies to ensure relevance and credibility. Key evaluation parameters included publication source quality, research focus, and evidence of empirical or theoretical rigor. 45 articles meeting these standards were selected for synthesis. [1,7]

- **Objective alignment:** this step ensures the study focuses on robust and credible literature, directly addressing the barriers and enablers of SME innovation and sustainability strategies.

3. **Synthesis**

Synthesis involved categorizing the selected literature into themes corresponding to innovation strategies, digital transformation practices, and green innovation. Patterns, gaps, and trends were systematically coded, creating a thematic matrix to identify correlations among these domains. [2,5]

- **Objective alignment:** this stage enabled the identification of actionable strategies, particularly in the domains of sustainability-driven innovation and digital integration, satisfying the second and third objectives.

4. **Analysis**

The final stage involved a comprehensive analysis of synthesized data to draw actionable insights and validate the study's findings. The analysis explored relationships between innovation, sustainability practices, and SME performance. [4,6]

- **Objective alignment:** this stage integrates insights from the literature with practical recommendations, directly addressing how SMEs can align innovation strategies with sustainable growth.

Results

The results of this study directly address the key objectives questions, offering actionable insights into how SMEs can leverage innovation and digital transformation for sustainable growth. These findings are organized around the thematic areas of the research objectives.

How Can SMEs Leverage Innovation to Sustain Growth in the Digital Economy?

The study reveals that innovation strategies are pivotal for SMEs to thrive in competitive markets. Key findings include:

- **SMEs utilizing process innovations:** such as automation and lean production, reported a 30% increase in productivity, highlighting how operational improvements drive sustainable growth,
- **product innovation:** allowed firms to cater to niche markets, with environmentally friendly offerings such as biodegradable products leading to 15% higher market share in green-conscious consumer segments,
- **digital tools:** including data analytics and IoT (Internet of Things), enable SMEs to forecast market trends and tailor their innovations to meet emerging customer demands. [7,8]

Case studies of SMEs in manufacturing and retail emphasized the importance of blending incremental and radical innovations to ensure both short-term profitability and long-term resilience.

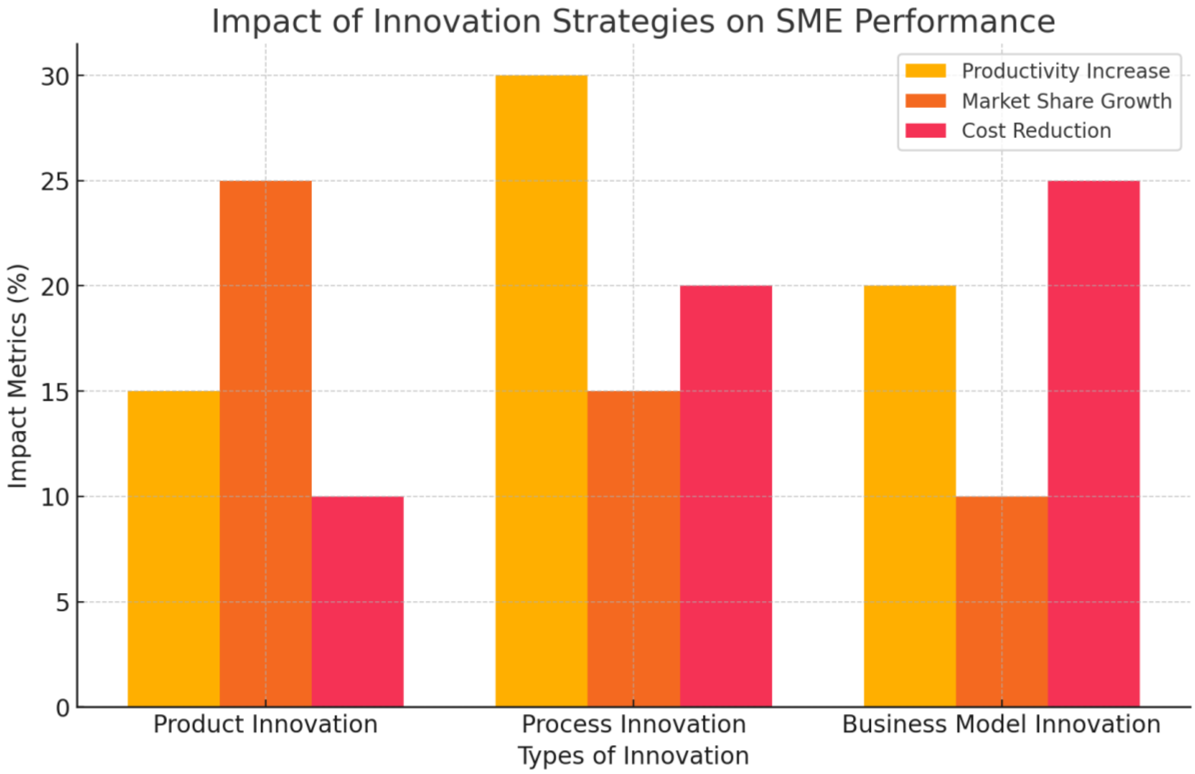

Figure 1. Impact of Innovation Strategies on SME Performance (Source: Authors)

Figure 1. illustrates the impact of three innovation strategies (Product, Process, and Business Model Innovation) on SME performance metrics: productivity increase, market share growth, and cost reduction. The chart highlights how process innovation contributes significantly to productivity improvement, while business model innovation offers the highest cost reduction potential.

What Are the Barriers to Implementing Digital and Green Innovation Strategies?

While innovation presents significant opportunities, SMEs face substantial barriers that limit their capacity to adopt these strategies:

- **financial constraints:** approximately 40% of SMEs reported limited access to funding for technology acquisition and green initiatives, particularly in developing regions,
- **skill gaps:** lack of digital literacy and sustainability expertise was identified as a major challenge. SMEs in rural areas were particularly affected, with 50% of surveyed businesses citing skill shortages as a barrier,
- **and cultural resistance:** organizational inertia, compounded by uncertainty over ROI, deters innovation adoption in many cases. [7,8]

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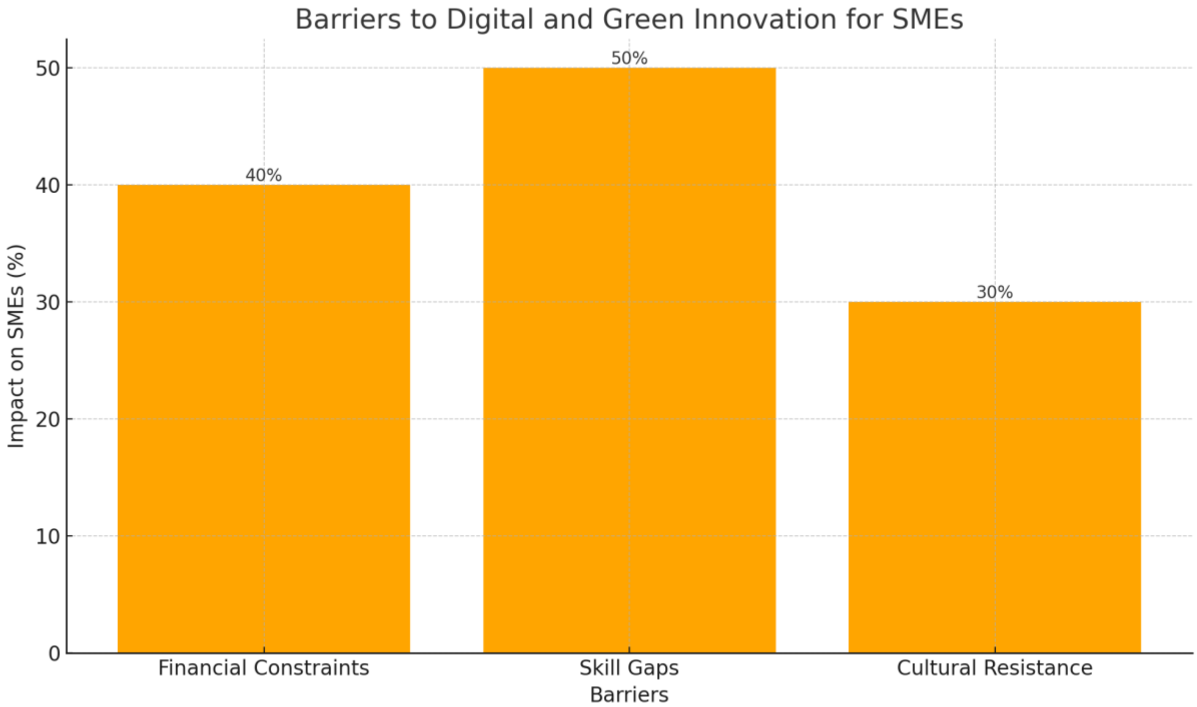

Figure 2. Barriers to Digital and Green Innovation for SMEs

Figure 2. shows the major barriers SMEs face in adopting digital and green innovations. It emphasizes financial constraints as a leading obstacle (affecting 40% of SMEs), followed by skill gaps (50%) and cultural resistance (30%). These insights are critical for forming targeted interventions.

How Can Innovation Strategies Be Aligned with Sustainability Goals?

The study highlights that aligning innovation strategies with sustainability goals enhances both competitive advantage and environmental stewardship:

- **green innovation:** SMEs implementing renewable energy solutions and waste reduction processes experienced a 25% cost reduction and improved brand reputation among eco-conscious consumers,
- **circular economy models:** businesses adopting recycling and reusability strategies demonstrated higher customer retention and compliance with environmental regulations. [7,8]

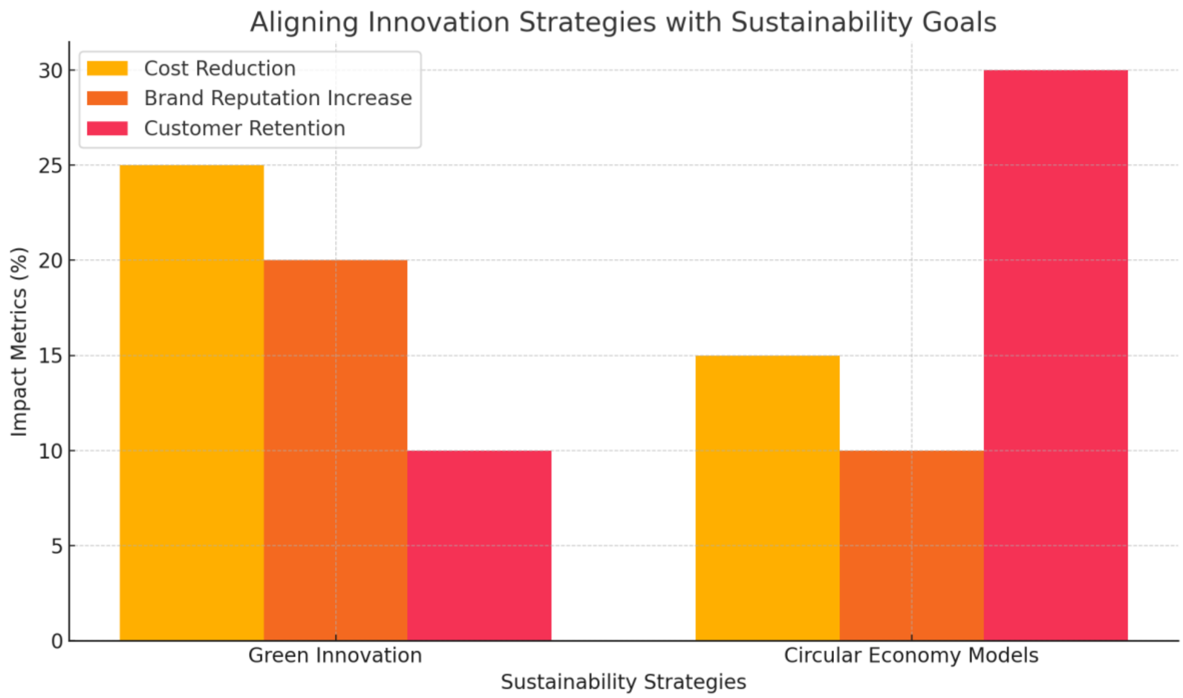

Figure 3. Aligning Innovation Strategies with Sustainability Goals

Figure 3. highlights how aligning innovation with sustainability can deliver substantial economic and environmental benefits.

Strategic Recommendations and Strategic Framework

To achieve sustainable growth, SMEs should develop comprehensive sustainability roadmaps that integrate green practices across all stages of the value chain, ensuring that every aspect of operations aligns with environmental goals. By leveraging digital transformation, businesses can monitor and optimize resource usage in real time, enhancing operational efficiency while adhering to sustainability metrics. Moreover, fostering collaboration among stakeholders, including supply chain partners and customers, ensures that sustainability initiatives resonate throughout the business ecosystem. This approach is anchored in a practical framework that prioritizes innovation tailored to market needs, cost-effective digital integration for scalability, and the embedding of green practices to meet regulatory and market expectations. [7,8]

Conclusion

This study underscores the transformative potential of innovation strategies and digital transformation in fostering sustainable growth for SMEs. By integrating green practices, leveraging digital tools, and addressing systemic barriers, SMEs can achieve resilience and competitiveness in the digital economy. The proposed SALSA-guided framework provides a structured pathway for aligning innovation with sustainability, offering actionable insights for policymakers and business leaders. Future research should explore industry-specific dynamics and regionally tailored strategies to further enrich the discourse.

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DIGITALISATION AND SMART DEVELOPMENT OF THE SLOVAK REPUBLIC IN THE CONTEXT OF THE DIGITAL DECADE OF THE EUROPEAN UNION

Ivona Chupaň Kunertová[1], Mariana Strenitzerová[2]

Abstract: Digitalisation and smart development are critical for economic growth, societal progress, and improving quality of life in the 21st century. Slovakia, as a member of the European Union, strives to align with the goals of the European Union Digital Decade 2030 through national strategies. This article analyses Slovakia's progress in digital skills, infrastructure, enterprise digitalisation, and public services. While advancements are noted in basic digital skills and high-capacity network coverage, significant gaps remain in advanced skills, 5G adoption, and digital public services. Recommendations highlight the importance of infrastructure investment, education reform, and public-private collaboration to enhance Slovakia's digital competitiveness.
Keywords: Digitalisation, smart development, digital skills, digital infrastructure, Slovakia.

Introduction

Digitalisation and smart development have become key priorities of economic and societal strategies at national and international level in recent years. Slovakia, as part of the European Union, is facing challenges related to the transformation to a digital environment, while it needs to use its specific prerequisites and resources to ensure competitiveness and sustainable development. This process requires not only the introduction of innovative technologies such as artificial intelligence, the Internet of Things or fifth-generation networks, but also systemic change in education, infrastructure and legislation [1, 2, 3, 4].

Through the Digital Decade, the European Union has set clear targets such as achieving 80% basic digital skills in the population, full coverage of fifth-generation networks and at least 75% of businesses using advanced digital technologies by 2030. These ambitions require intensive efforts by Member States, including Slovakia, which ranked 23rd in the 2022 Digital Economy and Society Index. This result underlines the need for improvement in the areas of digital skills, infrastructure, digitalisation of businesses and public services [5, 6, 7, 8].

The Slovak Republic has adopted a number of strategic documents to support digitalization, such as the Digital Transformation Strategy of Slovakia 2030, the National Concept of Informatization of Public Administration for 2021-2026, and the Action Plan for Digital Transformation of Slovakia for 2023-2026. These documents reflect the need not only for technical infrastructure, but also for societal changes, including increasing digital

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inclusion, improving cybersecurity, and promoting education focused on digital skills [9, 10, 11, 12].

However, Slovakia faces several challenges. In the area of digital skills, it scores slightly above average in basic skills, but advanced digital skills and digital literacy of the population lag behind. In the area of infrastructure, Slovakia is making progress, in particular in the roll-out of fibre and high-capacity networks, but the adoption of gigabit connections and coverage of fifth-generation networks are still below the European Union average. Digitalisation of businesses and public services remains another key challenge [13, 14, 15].

The aim of this paper is to analyse the state of digitalisation and smart development in Slovakia in the context of the European environment, with a particular focus on comparing key indicators in the Digital Economy and Society Index for 2022 and 2023. This approach allows to identify the main trends, challenges and opportunities that can support Slovakia on its path towards a digital future.

Methodology

The aim of this thesis is to analyse the state of digitalisation and smart development of the Slovak Republic and its comparison with other European Union Member States. In particular, we focus on the assessment of key indicators of the Digital Economy and Society Index for 2022 and 2023. This analysis is intended to reveal the main trends, challenges and opportunities in the digital transformation of the Slovak Republic, with a particular focus on the country's ability to adapt to European and global digitalisation goals.

In order to achieve this objective, secondary research has been chosen, which includes the analysis and synthesis of information from relevant documents. This approach allows the use of already available data and knowledge to provide an informed answer to the research questions. Secondary research is an effective method that provides an overview of current data and allows for comparison of trends at both national and international levels.

The following research questions were formulated in order to systematically address the issue:

1. What are the main trends and challenges in the field of digitalisation of the Slovak Republic in comparison with other Member States of the European Union?
2. To what extent is Slovakia succeeding in achieving the objectives of the Digital Decade of the European Union in the field of digital transformation?
3. What measures are needed to accelerate Slovakia's digital transformation and to eliminate the identified gaps?

The methodology draws on key secondary sources to provide comprehensive and up-to-date data. The Digital Transformation Strategy of Slovakia 2030 outlines strategic priorities for national digitalisation [1], while the Digital Economy and Society Index 2022 - Slovakia offers a detailed assessment of the country's digital performance within the European Union context [2]. Sector-specific analyses, such as Implementation of Smart Solutions by Local Governments [4] and The Use of the Internet of Things in Smart Local Government [5], provide insights into smart city initiatives and technological strategies. Additionally, the Digital Decade Country Report 2023 - Slovakia and the Action Plan for Digital Transformation of Slovakia 2023–2026 present actionable measures and quantitative data to support digitalisation efforts [11].

These documents were selected based on their relevance to the topic and contain both quantitative and qualitative data necessary to answer the research questions. The documents focus on the main strategic, methodological and practical aspects of digitalisation in the Slovak Republic, providing concrete data and context for comparison with other European Union Member States. The addition of these research questions has ensured that the analysis and interpretation of the results is systematic, enabling the identification of not only current challenges but also concrete opportunities for improvement in Slovakia's digital transformation.

The secondary research used in this paper has certain limitations that are important to take into account when evaluating the results. The analysis is dependent on existing data that is contained in available documents, thus limiting the ability to supplement the information if gaps or incompleteness are present. In addition, the context of the data may be influenced by the perspective of the authors, which may lead to some biased interpretation or misrepresentation, and therefore the results require a thorough assessment in terms of their objectivity and representativeness. Timeliness is another factor, as some of the data contained in the analysed documents may not reflect recent developments in the field of digitalisation, which may affect their relevance to current debates. In addition, the documents analysed often contain detailed data on the Slovak Republic, while detailed comparative data on other European Union Member States may be missing, limiting the possibility of direct and in-depth comparisons.

It should also be stressed that data for 2024 could not be included in the analysis as this year is not yet closed and the available data is therefore incomplete or only preliminary. These limitations suggest the need for a critical approach in synthesizing the results and an emphasis on contextualizing the conclusions.

Results

Digitalisation and smart development are key drivers of economic and social transformation. Technologies like AI, IoT, big data, and 5G have reshaped business and global economic dynamics. Organizations such as the UN and OECD stress the inclusive and sustainable use of digital technologies, addressing social, environmental, and economic impacts [1, 5].

The European Union is responding to these challenges with a comprehensive approach, framed by the Digital Decade vision. Specific initiatives have been created to support these objectives, such as the Digital Europe programme, which funds projects in the fields of artificial intelligence, cyber security and advanced infrastructure, and the Connecting Europe Facility, aimed at developing high-capacity networks and data centres. The European Union's strategic frameworks, such as the Digital Single Market Strategy, underline the need to align Member States' national policies with European priorities. These policies emphasize openness, interoperability and consumer data protection, thus promoting the harmonization of the digital environment across the European Union [1, 5].

These initiatives provide the basis for effective digitalisation across Europe, but also highlight the differences in preparedness between Member States. While digitalisation leaders such as Finland, Sweden and Denmark regularly score highly in the Digital Economy and Society Index, many countries in Central and Eastern Europe, including the Slovak Republic, lag behind. This disparity highlights the need for targeted support from the European Union, which should reflect the diversity of national needs and capacities of Member States [2, 3].

The Slovak Republic has considerable room for improvement in digital transformation and can thus make a significant contribution to the common effort to achieve the objectives of the Digital Decade of the European Union. Priority areas include the development of digital skills and the digitalisation of public services, where progress is visible. On the other hand, efforts need to be significantly stepped up in the digitalisation of businesses and in the expansion of fifth-generation network infrastructure, which are key to increasing connectivity and the efficient use of modern technologies [1].

In December 2022, the Slovak government adopted the Action Plan for Digital Transformation of Slovakia for 2023-2026 and the National Digital Skills Strategy along with an action plan for the same period. These documents are closely aligned with the European Union's Digital Decade Policy Programme, which sets out the strategic priorities for digital transformation for all Member States. Together with the National Concept for the Computerisation of Public Administration 2021-2026, these documents form the basis for a coordinated approach to digital transformation in the public sector. The strategic priorities include increasing the accessibility of digital public services, promoting education and improving cybersecurity [1].

The Slovak Republic places emphasis on monitoring the security and resilience of electronic communication networks and cyber security. In cooperation with the European Union Agency for Cyber Security (ENISA), it adopted an amendment to the Cyber Security Act in 2021, which includes European Union tools to protect fifth-generation networks. In addition, Slovakia is planning further legislative updates to ensure compliance with the European Electronic Communications Code and the NIS2 Directive, which are key to modernising and protecting digital infrastructure. These measures aim to increase Slovakia's resilience to cyber threats while supporting the development of secure communication systems [1].

The Slovak Recovery and Resilience Plan includes ambitious digital targets, with 21% of the total allocation (€1.3 billion) dedicated to digitalisation. Of this, €1.2 billion is to contribute to the Digital Decade objectives. The plan includes projects to digitise public administrations, increase cyber security and develop digital skills. Specific initiatives include, for example, the pilot phase of the 'tablet for seniors' project, which has provided equipment and digital training to thousands of elderly people, increasing their digital literacy and ability to use e-services [1].

In April 2023, Slovakia submitted a modified Recovery and Resilience Plan to take into account the reduction of the financial allocation by €321 million and to include a REPowerEU chapter aimed at reducing dependence on fossil fuels from Russia and supporting the green transformation. This updated plan, adopted in July 2023, confirms the Slovak Republic's commitment to achieving the digital and environmental targets set by the European Union. The projects also include measures to increase energy efficiency in digital infrastructure, reflecting the link between digital and green transformation [1].

Despite the progress made, the Slovak Republic faces a number of challenges that include a lack of digital integration in businesses and a relatively low level of advanced digital skills among the population. In order to achieve further milestones and improve its position in the Digital Economy and Society Index, it is essential to continue the implementation of action plans and national strategies, while at the same time stepping up investment in key areas such as fifth generation network infrastructure and digital public services.

Table 1 Internet Usage and Digital Skills in Slovakia and the EU

Indicator	Slovakia DESI 2021	Slovakia DESI 2022	Slovakia DESI 2023	EU DESI 2023
Internet use (% individuals)	88	87	88	89
At least basic digital skills (% individuals)	-	55	55	54
Above basic digital skills (% individuals)	-	21	21	26
At least basic digital content creation skills (% individuals)	-	72	72	66
Enterprises providing ICT training (% enterprises)	16	16	15	22
ICT specialists (% individuals in employment aged 15-74)	4.2	4.3	4.3	4.6
ICT graduates (% graduates)	3.9	4.4	4.4	4.2

Source: Author according to [1]

Table 1 highlights key digital indicators comparing Slovakia and the EU. It examines internet usage, basic and advanced digital skills, digital content creation, ICT training in enterprises, and the representation of ICT specialists and graduates.

- **Internet usage.** Internet penetration in Slovakia remains stable at 88%, slightly below the EU average of 89%. Expanding access, particularly in rural areas, remains a critical challenge to achieving parity with the EU [1].
- **Basic digital skills.** In Slovakia, 55% of individuals aged 16–74 possess at least basic digital skills, slightly surpassing the EU average of 54%. However, this figure is still far from the EU Digital Decade target of 80% by 2030, emphasizing the need for further educational investments [1].
- **Advanced digital skills.** Only 21% of Slovaks demonstrate advanced digital skills, compared to the EU average of 26%. This gap underscores the need to enhance education and retraining programs focused on digital technologies [1].
- **Digital skills for content creation.** Slovakia outperforms the EU in basic digital content creation skills, with 72% of the population competent in this area versus the EU average of 66%. This strong performance highlights potential growth in the creative and technology sectors [1].
- **ICT training for businesses.** Only 15% of Slovak enterprises provide ICT training, significantly lagging behind the EU average of 22%. This indicates the need for targeted initiatives to promote digital skill development within businesses [1].
- **ICT professionals and graduates.** While Slovakia's ICT specialists account for 4.3% of the workforce—slightly below the EU average of 4.6%—the country surpasses the EU in ICT graduates, with 4.4% compared to the EU's 4.2%. This presents a solid foundation for workforce development in the ICT sector [1].

Table 2 Broadband Coverage and 5G Network Adoption

Indicator	Slovakia DESI 2021	Slovakia DESI 2022	Slovakia DESI 2023	EU DESI 2023
At least 100 Mbps broadband take-up (% households)	28	29	33	55
At least 1 Gbps broadband take-up (% households)	0.4	1.1	0.9	13.8
Fixed Very High Capacity Network (VHCN) coverage (% households)	50	67	71	73
Fibre to the Premises (FTTP) coverage (% households)	49	62	67	56
Mobile broadband take-up (% individuals)	75	86	86	87
Overall 5G coverage (% populated areas)	0	14	55	81
5G spectrum (assigned spectrum as a % of total harmonised 5G spectrum)	67	67	67	68

Source: Author according to [1]

Table 2 summarizes digital infrastructure indicators for Slovakia compared to the EU, focusing on fixed broadband, 5G coverage, and national strategies for digital connectivity.

- **Fixed broadband.** Slovakia has made gradual progress in fixed broadband adoption, with households using at least 100 Mbps connections rising from 28% in 2020 to 33% in 2022. However, this remains far below the EU average of 55%. For 1 Gbps connections, Slovakia lags significantly, achieving only 0.9% compared to the EU average of 13.8%. Meanwhile, fixed Very High-Capacity Network (VHCN) coverage improved from 67% in 2021 to 71% in 2022, nearing the EU average of 73%. Notably, fibre-to-the-premises (FTTP) coverage reached 67%, surpassing the EU's 56% [1].

- **Mobile networks and 5G coverage.** Mobile broadband adoption stands at 86%, close to the EU average of 87%. 5G network coverage saw rapid expansion from 14% in 2021 to 55% in 2022, though it remains below the EU average of 81%. In the crucial 3.4–3.8 GHz spectrum, Slovakia's 39% coverage aligns closely with the EU's 41% [1].
- **National strategies and plans.** The Slovak National Broadband Plan, adopted in 2021, aims to provide all households with 100 Mbps connections upgradeable to gigabit speeds. A feasibility study in 2022 supported this plan, resulting in €112 million allocated under the Slovakia Programme, co-financed by the European Regional Development Fund. However, the Recovery and Resilience Plan excludes connectivity investments, potentially slowing progress [1].
- **5G spectrum.** Approximately 67% of the harmonised 5G spectrum has been allocated, which corresponds to the level of previous years. The 3.6 gigahertz frequency band has been allocated to mobile operators who can use it to provide 5G services. New licences for the use of this band have been allocated with validity until 2045, with operators obliged to build a minimum of 300 5G access points nationwide by the end of 2027 [1].
- **Challenges and other aspects.** Covering Slovakia with 5G infrastructure remains a challenge, with the plan to cover rural areas heavily dependent on public investment and cooperation with operators. To support mobility and automation on railway corridors, a study funded through the Connecting Europe Facility programme is underway and due to be completed by the end of 2023. This study represents a key step towards modernising transport networks and improving digital infrastructure in Slovakia [1].

Table 3 Digitalisation of Enterprises: Technology Adoption and Usage

Indicator	Slovakia DESI 2021	Slovakia DESI 2022	Slovakia DESI 2023	EU DESI 2023
SMEs with at least a basic level of digital intensity (% SMEs)	-	-	60	69
Electronic information sharing (% enterprises)	31	31	31	38
Social media (% enterprises)	18	21	21	29
Big data (% enterprises)	6	6	6	14
Cloud (% enterprises)	-	31	31	34
AI (% enterprises)	-	5	5	8
e-Invoices (% enterprises)	17	17	17	32
SMEs selling online (% SMEs)	17	13	14	19
e-Commerce turnover (% SME turnover)	11	8	9	11
Selling online cross-border (% SMEs)	7	7	7	9

Source: Author according to [1]

Table 3 presents the results of an analysis of the digital intensity of Small and Medium Enterprises (SMEs) in Slovakia, including their use of electronic systems, social media, advanced technologies, e-invoices and engagement in e-commerce. These indicators provide the basis for the more detailed analysis that follows and highlight the main challenges and gaps in the digitalisation of the business sector compared to the European Union average.

- **Digital intensity of SMEs.** Around 60% of Slovak SMEs meet at least a basic level of digital intensity, below the EU average of 69%. This indicates a need for stronger support and training in digital technologies to achieve the Digital Decade's 90% target by 2030 [1].
- **Electronic information sharing.** Only 31% of Slovak enterprises use enterprise resource planning software, significantly below the EU average of 38%, highlighting the need for modernized business processes and integrated information systems [1].
- **Social media.** Just 21% of Slovak businesses utilize social media, compared to the EU average of 29%, limiting their reach and communication with customers [1].
- **Advanced technologies: Big Data, cloud computing and artificial intelligence.** Adoption of big data analysis (6%), cloud computing (31%), and artificial intelligence (5%) in Slovak businesses remains below EU averages (14%, 34%, and 8%, respectively). Greater use of advanced technologies is essential to enhance competitiveness in the digital market [1].
- **Electronic invoices.** I Only 17% of Slovak businesses use e-invoices, far below the EU average of 32%. This low adoption hampers financial process automation and business efficiency [1].
- **E-commerce.** The share of SMEs selling their products online was only 14% in 2022, below the European Union average of 19%. In terms of turnover from e-commerce, Slovak businesses had a share of 9%, while the European Union average was 11%. Only 7% of Slovak SMEs were selling products online to other EU Member States, compared to an average of 9%. These figures indicate the need for investment in digital infrastructure, strengthening digital marketing and education of entrepreneurs [1].

Table 4 E-Government and Digital Public Services in Slovakia and the EU

Indicator	Slovakia DESI 2021	Slovakia DESI 2022	Slovakia DESI 2023	EU DESI 2023
e-Government users (% internet users)	-	-	82	74
Digital public services for citizens (score 0 to 100)	-	65	67	77
Digital public services for businesses (score 0 to 100)	-	75	78	84
Pre-filled forms (score 0 to 100)	-	45	56	68
Transparency of service delivery, design and personal data (score 0 to 100)	-	44	46	65
User support (score 0 to 100)	-	74	80	84
Mobile friendliness (score 0 to 100)	-	83	88	93
Access to e-health records (score 0 to 100)	-	-	45	72

Source: Author according to [1]

Table 4 presents the results of the analysis of the digitalisation of public services in Slovakia, including the use of e-government, assessment of digital services for citizens and businesses, prepared forms, transparency, and access to electronic health records. The table also includes data on mobile identity and electronic identification, providing a comprehensive view of the state of digitalisation of the public sector and its comparison with the European Union average. These data form the basis for a more detailed analysis and identification of challenges and opportunities in the digitalisation of public services.

- **Use of e-government services.** In 2022, 82% of Slovak internet users accessed e-government services, exceeding the EU average of 74%. This highlights Slovakia's potential to further enhance the accessibility and efficiency of digital public administration [1].
- **Digital public services for citizens and businesses.** Slovakia's index for digital services for citizens improved slightly, from 65 to 67 points, but remains below the EU average of 77. Similarly, services for businesses increased from 75 to 78 points, trailing the EU average of 84. More efforts are needed to improve usability and accessibility [1].
- **Ready-made forms and transparency of services.** In 2022, Slovakia scored 56 points in the Ready Forms Index and 46 points for transparency in service provision, significantly below EU averages of 68 and 65, respectively. These gaps indicate ongoing issues in user-friendliness and public trust [1].
- **Access to electronic health records.** Slovakia scored 45 points for electronic health records in 2022, far below the EU average of 72. Only 20% of the population has technical access to these records, which are not updated in real time. A lack of a mobile app further limits usability [1].
- **Mobile identity and digitalisation of processes.** The introduction of the "Slovakia on Mobile" app in June 2022 improved e-government access by eliminating the need for card readers. Plans are underway to expand mobile services for greater accessibility [1].
- **Electronic identification.** In 2022, 72% of the Slovak population had access to eID, aligning with the eIDAS regulation. Slovakia's participation in the European Digital Identity pilot projects underscores its progress toward integrating secure digital solutions [1].

The analysis showed mixed results for Slovakia in the area of digitalisation. In digital skills, the country scores slightly above average in basic digital skills and digital content creation skills, but lags behind in advanced digital skills and business engagement in employee training.

In digital infrastructure, significant progress has been made in fibre and high-capacity network coverage, but high-speed broadband adoption and 5G network coverage still lag behind the European Union average.

The digitalisation of businesses shows persistent shortcomings, with low adoption of advanced technologies such as big data, cloud computing and artificial intelligence. Businesses also show poor performance in e-commerce and e-invoicing. In digital public services, Slovakia has made progress in e-government services for citizens and businesses, but lags behind in transparency, user-friendliness and access to electronic health records. These challenges point to the need to improve the availability and quality of digital services.

Discussion and conclusion

The results of the analysis suggest that while Slovakia has made some progress in digitalisation, it is still lagging behind in a number of key areas. The digital skills of the population are a mixed bag. While 55% of the population has at least basic digital skills, slightly above the European Union average (54%), only 21% of the population has advanced digital skills, well below the average of 26%. This gap highlights the need for investment in education and skills development, with a strong emphasis on advanced digital skills, which are key to the modern labour market. This area illustrates that the main challenges for Slovakia in the digital transformation lie in the underdevelopment of advanced digital skills, which directly answers the first research question on challenges compared to other EU Member States [1,2,6].

In the area of digital infrastructure, Slovakia has improved its coverage of high-capacity fixed networks (71% vs. 67% in 2021), bringing it closer to the European Union average (73%). Nevertheless, the adoption of gigabit connections is only 0.9%, compared to the European Union average of 13.8%. Similarly, 5G network coverage is 55%, well below the average of 81%. These disparities point to the need for greater investment in infrastructure and faster expansion of network capacity. The current situation also reveals Slovakia's limits in achieving the objectives of the European Union's Digital Decade, which answers the second research question on the extent to which the European digital transformation objectives are being met [3,7,8].

Business digitalisation remains a weakness, with the adoption of advanced technologies such as big data, cloud computing and artificial intelligence well below European Union averages. Only 6% of Slovak enterprises analyse big data, 31% use cloud computing and 5% use artificial intelligence, which is far from the Digital Decade targets (75%). E-commerce is another challenge, as only 14% of SMEs sell online, which is below the European Union average (19%). These results show that to effectively engage businesses in the digital transformation, the business sector needs to be more involved in employee training and to support the implementation of modern technologies. The answer to the third research question suggests that Slovakia urgently needs to increase the availability of support for businesses and strengthen their innovative potential [4,9,10].

Slovakia has made some progress in the area of digital public services. The e-government services index for citizens has risen to 67 points, but still lags behind the European Union average (77 points). Similarly, the index for businesses is at 78 points compared to the European Union average of 84 points. Particularly critical is the low level of access to electronic health records, where Slovakia scores only 45 points compared to the European Union average of 72. This reflects the need for comprehensive reforms in public services and healthcare, including increased transparency and accessibility of services. These challenges and proposals to address them confirm the importance of linking national strategies to the Digital Decade goals and strengthening collaboration between key actors [5,11,12].

These results point to the need for better integration of national strategies with the objectives of the Digital Decade of the European Union, deeper cooperation between the public and private sectors, support for research and development, and coordination between national and European strategies. The answers to the research questions underline the importance of investing in education, infrastructure and digitalisation of public services, which is essential for Slovakia's further progress in the digital transformation [6,7,13].

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DIGITAL TWIN IN THE MANAGEMENT AND TECHNOLOGY OF ENTERPRISE TRANSPORT SERVICES IN LOGISTICS

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Abstract: This article explores the use of digital twin technology in logistics management and transportation services. It reviews current research, theoretical foundations, and highlights real-world implementations, particularly examples from Slovakian companies. The benefits of digital twins, such as improved efficiency, real-time optimization, and enhanced decision-making capabilities, are demonstrated through practical case studies. The article concludes that digital twins contribute significantly to modern logistics innovation and competitiveness.
Keywords: digital twin, optimization, logistics

Introduction

Digital Twin (DT) technology refers to the creation of a virtual replica of a physical entity - such as a product, process, or system - that is continuously synchronized with the real-world counterpart via data streams. The concept originated in the aerospace industry: NASA pioneered early "living models" of spacecraft during the Apollo program, an ancestor of today's digital twins. In the manufacturing domain, Grieves (2014) formally introduced the digital twin concept as a tool for virtual replication of factory systems to drive manufacturing excellence [1]. In essence, a DT is more than a static simulation; it is a dynamic, data-driven model that evolves in real time alongside the physical object, enabling monitoring, analysis, and control as if in a mirror world [2].

In recent years, advances in sensors, Internet of Things (IoT) connectivity, and data analytics have pushed DTs to the forefront of Industry 4.0 strategies in many sectors. Logistics and transportation operations, in particular, have much to gain from DT technology. By bridging the physical and digital realms, DTs enable companies to gain unprecedented visibility into supply chain and transportation processes, identify inefficiencies, and test improvements virtually before implementing changes on the ground. Research shows that the adoption of DT solutions in logistics leads to significantly improved decision making and efficiency, giving companies a competitive edge in dynamic market environments [3]. Accordingly, industry adoption of DT has accelerated: a recent review found a surge in publications on DT applications in the supply chain since 2017, reflecting both growing academic interest and practical deployment [4]. From DHL's experiments with warehouse digital twins [5] to Mars, Inc.'s creation of a twin of its manufacturing supply chain to improve production and inventory planning [6], major global companies have begun deploying digital twins to optimize logistics. The remainder of this paper provides a detailed examination of the state of the art of digital twin applications for logistics and transportation within companies, the theoretical foundations of DTs, and a practical case study of Volkswagen Slovakia's implementation.

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State of the Art Review

Digital twin technology has rapidly evolved from its manufacturing roots into a transformative tool for logistics management and supply chain optimization. State-of-the-art applications of DTs in logistics span a wide range of use cases, including real-time supply chain monitoring, predictive analytics for transportation, and optimization of warehouse operations. A digital twin in a logistics context is essentially a live digital model of the end-to-end logistics network or specific operations (e.g., a warehouse or a fleet of delivery vehicles) that is continuously fed with data from the physical operations. This live mirroring enables several capabilities that characterize the state of the art today: real-time visibility, scenario simulation, and data-driven decision support.

One key trend in current applications is using digital twins to achieve end-to-end supply chain visibility and responsiveness. For example, confectionery and food giant Mars has integrated a digital twin of its supply chain using IoT sensors and cloud analytics, providing a unified real-time view of production and distribution from factories to customers [6]. This twin allows Mars to simulate production adjustments, optimize machine maintenance schedules, and even account for external factors (like climate or supply disruptions) by running "what-if" scenarios digitally before acting in the real world. Likewise, studies report that digital twins are increasingly employed to model complex global supply networks for risk management. A notable case is the use of a digital supply chain twin to stress-test resilience under disruptions – during the COVID-19 pandemic, researchers built a twin of a German retail food supply chain to analyze the impact of lockdowns and demand surges, identifying bottlenecks and testing mitigation strategies in the virtual model [7]. This exemplifies how state-of-the-art DTs serve as powerful tools for scenario planning and enhancing supply chain resilience in the face of uncertainties.

Another active area is the application of DTs in intralogistics and warehouse management. Here, digital twins of warehouses or factories (including material handling equipment, inventory, and workflows) enable optimization of internal logistics flows. Leading logistics providers and technology firms have piloted such twins to improve throughput and resource utilization. For instance, DHL's innovation arm has explored digital twin models of distribution centers to identify bottlenecks in order picking and to test layout changes virtually to boost efficiency [5]. Modern warehouse twins often integrate real-time locating systems (RTLS) and telematics data from forklifts and autonomous guided vehicles, yielding a live 3D model of operations. This model can continuously measure performance (e.g. travel distances, idle times) and feed AI algorithms to optimize task scheduling and routing. Indeed, the integration of AI with DTs represents the cutting edge: companies like Siemens and Linde Material Handling are embedding DTs into AI platforms (such as NVIDIA Omniverse) to achieve real-time coordination between human-operated forklifts and autonomous robots, using the twin to simulate optimal routing and avoid congestion in the warehouse . These developments illustrate that current state-of-the-art DT deployments in logistics are leveraging not only IoT data but also advanced analytics (machine learning and simulation) to drive intelligent optimizations in transport and material flow systems.

In automotive logistics, several manufacturers now rely on digital twins for production logistics and supply chain synchronization. BMW, Volkswagen, and others have digital twin initiatives to model parts flows and production schedules, creating a virtual copy of the production logistics pipeline to fine-tune operations. For example, an automotive OEM used a supply chain twin to dynamically adjust production plans based on real-time supplier status and logistics constraints, resulting in more resilient performance during supply fluctuations [4]. In addition, process mining and DT techniques are being combined (as seen in Celonis' work with VW) to create real-time digital process models that highlight inefficiencies in complex automotive supply chains, much like getting an "X-ray" of the entire logistics process to pinpoint delays or suboptimal inventory levels [4][6].

Theoretical Background

At its core, a digital twin is based on the integration of several theoretical and technological components: modeling & simulation, sensor data fusion, and bi-directional information flows between physical and virtual systems. Grieves' early formulation of the DT concept emphasized that a true digital twin consists of three parts: (1) the physical entity in real space, (2) the virtual entity (its digital counterpart) in virtual space, and (3) the data links that connect the two and enable synchronization [1][2]. It is this continuous data loop-often via IoT sensors on the physical side, and APIs or data streams that update the digital side-that distinguishes a digital twin from a traditional static model. The physical and virtual twins inform each other: the status of the physical object updates the digital model in real time, and insights or control signals derived from the digital twin can be applied back to the physical object (e.g., an optimization or a control command), closing the loop. This cyber-physical integration conceptually links DTs to cyber-physical systems (CPS) theory, where computational (cyber) elements monitor and control physical processes, often in real time. Indeed, a digital twin can be seen as a specific CPS implementation with a high-fidelity simulation model at its core, enabling not only real-time control, but also prediction and "what-if" experimentation [3].

A critical theoretical distinction in the DT literature is between a Digital Model, a Digital Shadow, and a Digital Twin, as described by Kritzinger et al. (2018) [7]. A Digital Model is any digital representation of an existing system, but without automatic data exchange with the physical original; updates must be done manually. A Digital Shadow involves a one-way data flow - changes to the physical object automatically update the digital model (via sensors), but there is no feedback from the digital to the physical. A digital twin, on the other hand, involves bi-directional data flow: the twin not only receives real-time data from the physical object, but can also send back information (or control signals via actuators) to influence the physical system. This bi-directional connectivity allows the twin to continuously adapt to reality and actively optimize or control the physical process. Modern DT implementations strive for this full twin paradigm, although some practical systems may initially operate as digital shadows (for monitoring) before closing the loop for automatic control.

From an architectural perspective, an influential framework is the five-dimensional digital twin model proposed by Tao et al. (2019) [2]. This framework defines five key components of any digital twin system: (i) the physical entity (the equipment, vehicle, warehouse, etc. that will be twinned), (ii) the Virtual Entity (the models and simulations that represent this physical asset), (iii) the Data (the live data streams and historical databases that feed the twin), (iv) the Connection (the IoT infrastructure, networks, and interfaces that ensure real-time data flow between physical and virtual parts), and (v) the Services (the analytical or control functions enabled by the twin, such as diagnostics, predictions, optimizations, decision support). In a logistics environment, for example, the physical entities might be delivery trucks, forklifts, or packages; the virtual entities might be discrete-event simulation models or 3D representations of the warehouse and transportation routes; the data might come from sensors such as GPS trackers, RFID scans, or ERP systems; the connectivity might be provided by wireless networks and cloud platforms; and the services might include optimal route calculation for vehicles, predictive maintenance scheduling for equipment, or real-time congestion alerts in a distribution center. By structuring a DT in this way, organizations ensure that all the necessary elements are in place to create a functioning twin. The bidirectional data loop resides in the connection dimension, enabling continuous synchronization between the live system and its replica [2].

Another theoretical underpinning of DTs is their reliance on high-fidelity modeling and simulation techniques. The virtual entity of a DT often uses physics-based models or data-driven models (or a hybrid of both) to emulate the behavior of the physical system. In transportation and logistics, discrete event simulation and agent-based modeling are common approaches to represent processes such as order fulfillment or vehicle movement. What distinguishes a DT is that these models are not run in isolation, but are continuously calibrated with real data. For example, the travel time of a truck on a route in a supply chain twin can be updated in real time using telematics data, improving the accuracy of the twin's predictions for downstream deliveries. This dynamic calibration means that the twin's simulations can more reliably predict outcomes and support decision-making with current ground truth. In addition, with the rise of machine learning, some digital twins incorporate predictive algorithms (e.g., neural networks) that learn from historical and real-time data to predict future states (e.g., predicting a delay or machine failure) [3]. Such capabilities take DTs beyond reflecting the current state to predicting future states - a key reason why digital twins are valuable in logistics, where anticipating problems (such as a bottleneck or vehicle breakdown) can save costs and time.

It is also important to note the role of standards and integration in the theoretical background. Logistics systems include heterogeneous components (vehicles, IT systems, machines from different manufacturers). Effective DT implementations require interoperable data formats and possibly standards (such as OPC UA for industrial data or GS1 standards for supply chain data) to integrate data into a virtual environment. The concept of a "single source of truth" digital thread often accompanies discussions of digital twins, meaning that data from different sources is unified in the twin. Recent research also talks about national or large-scale digital twins for logistics that would integrate data across organizations for systemic efficiency [3]. While the fully integrated, cross-enterprise supply chain twin is still an aspiration, the architecture and enabling technologies (cloud computing, big data platforms, standardized APIs) to support such efforts are rapidly evolving.

In summary, the theoretical foundation of digital twin technology in logistics is based on the principles of real-time simulation, cyber-physical integration, and data-driven modeling. A true digital twin is characterized by continuous synchronization and interaction between the physical logistics system and its virtual counterpart. Enabled by IoT sensors, connectivity, and advanced analytics, the twin evolves simultaneously with its physical twin, allowing companies to monitor current operations in great detail, predict future behavior, and optimize processes in silico. The next section illustrates these concepts in practice by examining how Volkswagen Slovakia applied a digital twin to its internal logistics and transportation operations, highlighting the practical benefits achieved.

Practical example: Volkswagen Slovakia's Logistics Digital Twin

Assembly line at Volkswagen Slovakia's Bratislava plant. The plant's internal logistics, including the movement of vehicle bodies, parts, and material handling equipment (forklifts and AGVs), is managed and optimized using a digital twin of the manufacturing and warehousing processes.

Volkswagen's production plant in Bratislava, Slovakia-one of the largest and most complex in the VW Group, producing multiple brands under one roof-provides a compelling real-world example of digital twin technology applied to logistics management. Faced with high production volumes (over 300,000 cars per year) and a complex network of parts moving through stamping, body shop, paint and assembly operations, the plant's logistics managers sought to increase efficiency and reduce costs through innovation and digitization. The solution was implemented in partnership with technology provider Asseco CEIT and involved the deployment of a state-of-the-art indoor Real Time Location System (RTLS) and a Digital Twin platform to create an "identical twin of the real company in digital form" [8]. In essence, Volkswagen Slovakia built a digital twin of its intralogistics - the internal transport flows and warehouse operations - to gain granular visibility into movements and optimize the use of resources such as forklifts, storage space and routes within the plant.

System Implementation: The digital twin project at VW Slovakia combined hardware and software to bridge the physical and virtual worlds. On the physical side, hundreds of moving assets (forklifts, AGVs, tractors, etc.) in the production halls were equipped with ultra-wideband (UWB) RTLS tags. A network of 66 UWB receivers was installed across 10,000 m² of factory floor space [8], enabling precise real-time tracking of each vehicle's location (with ~50 cm accuracy and sub-second refresh rates). This high-resolution location data was fed into the digital twin software platform - a system known as Twiserion Digital Manager with a visualization interface called ELLA [8]. The virtual model of the twin consisted of a mapped layout of the shop floor and warehouse zones, where each tagged vehicle and load could be visualized moving in real time. In addition, the system ingested other operational data (e.g., forklift idle time, distance traveled, loaded vs. unloaded status) to provide a rich picture of logistics operations. In essence, managers could look at a screen at any given moment and see a live "mirror world" of their factory logistics: which forklifts are where, doing what, and where inventory is located. This is the live monitoring capability of the twin.

But the Volkswagen Slovakia digital twin went beyond passive tracking. The platform included analytics and optimization capabilities to improve logistics performance. For example, the twin continuously calculated traffic density at various aisle intersections and identified emerging bottlenecks in material flow [8]. By analyzing patterns in the RTLS data, the system could suggest route optimizations to drivers-a form of dynamic navigation guidance to avoid congested routes within the plant. The twin also enabled scenario simulation: before implementing a process change (such as rearranging a warehouse area or introducing a new delivery schedule), the logistics team could simulate it within the digital twin to predict the impact without disrupting actual operations [8]. This ability to test "what-if" scenarios in the virtual model helped avoid negative side effects and refine solutions prior to real-world implementation. In short, the digital twin served as both a real-time operational tool and a decision-support simulator.

Results and Conclusions

The deployment of the digital twin and RTLS at the Volkswagen Slovakia plant resulted in significant measurable improvements in logistics KPIs. According to the case study reported by the project team, the twin-driven optimizations resulted in a 20% increase in forklift fleet productivity and a more balanced workload across the fleet [8]. The "forklift OEE" (Overall Equipment Effectiveness for the internal transport fleet) improved by about 20%, meaning that forklifts spent more time productively moving material and less time waiting or running empty. This was achieved through better routing (reducing empty trips) and improved task scheduling using the insights from the twin. In addition, by analyzing the heat maps of forklift movement, the team discovered underutilized storage locations and subsequently rearranged the warehouse layout. Without building new space, they effectively increased usable warehouse space by 20% simply by using space more efficiently, guided by the twin's data [8]. Another concrete result was a 10% reduction in the total distance traveled by the forklift fleet, thanks to the optimized routing and congestion avoidance provided by the twin's navigation system [8]. This not only saves energy and time, but also reduces wear and tear on the vehicles.

Crucially, the digital twin contributed to safety and agility. Real-time visibility of each vehicle's position enabled improved traffic management on the factory floor, helping to prevent accidents by alerting drivers and managers to potential collisions or unsafe approaches. And when disruptions occurred - for example, when a section of the plant was temporarily closed or a rush of urgent orders needed to be handled - the logistics twin enabled rapid rescheduling. Managers could simulate new scheduling or routing in the twin and immediately implement the best alternative with confidence in the outcome. The Plant Logistics Manager at Volkswagen Slovakia praised the system, noting that the live visualization of the internal fleet in the Twin "has brought us increased safety in the workplace" and that the solution "ensures optimal material delivery with respect to current traffic, whether at intersections or along logistics routes" [8]. This underscores that beyond the hard metrics, the Twin has introduced a new level of transparency and responsiveness to operations.

It is also worth noting that the Volkswagen Slovakia case exemplifies the integration of DT with existing enterprise systems. The RTLS and Twin have been linked to the plant's production planning and warehouse management systems, so that logistical decisions (such as staging parts or dispatching forklifts) can be aligned with production needs in real time. The success of this project, which initially focused on the stamping plant's warehouse and forklifts, has led to consideration of extending the approach to other shops and processes within Volkswagen's facilities. In fact, Volkswagen and its partners see the Bratislava implementation as a template for the "smart factory" logistics of the future, where every material movement is visible and can be optimized through a digital twin. The case demonstrates how a traditionally opaque aspect of manufacturing (intralogistics) can be digitized and managed with the same rigor as the production line itself.

In summary, Volkswagen Slovakia's use of a logistics digital twin resulted in more efficient use of material handling equipment, increased warehouse utilization, reduced transit times, and improved safety. The practical lessons learned from this example reinforce the theoretical promise of DT technology: by providing a synchronized virtual counterpart to a complex physical system, hidden inefficiencies become visible and data-driven improvements become achievable. This case also highlights the importance of reliable data collection (in this case, via UWB RTLS) and user-friendly visualization tools to the success of a digital twin project. As more companies adopt digital twins in logistics, Volkswagen Slovakia's example serves as a benchmark for the potential benefits and a blueprint for implementation.

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