Leveraging Digital Twin Technology for Logistics Optimization in Manufacturing SMEs

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Leveraging Digital Twin (DT) Technology for Logistics Optimization in Manufacturing SMEs

Abstract

Purpose: The study is centred on how DT technology assists logistics processes by SMEs in realising high performance, cost reduction, and assistance in making acceptable choices. The primary goal of the paper is to develop a pragmatic framework in which SMEs can use DT in a cost-effective and non-rigid way.

Design/Methodology/Approach: The research methodology consists of a qualitative case study that explores case studies, peer-reviewed research articles available at various sources, such as Web of Science, Scopus and Google Scholar, as well as market reports available at various sources, such as Statistics Canada and markets.

Findings: The research proved that DT technology has the potential to increase production efficiency by streamlining logistics, maximising resources for more efficient operations, and minimising downtime.

Research Limitations/Implications: The study has the limitation of using the previous literature, case studies, and research papers as the main sources of information, which do not necessarily reflect SMEs currently taking advantage of the DT technology in logistics.

Practical Implications: The study gives SMEs insights into implementing the DT technology to streamline logistics, lower costs, and enhance efficiency.

Social Implications: Social implications of the presented research are significant as they reflect the opportunity of utilizing DT technology to increase sustainability among SMEs in terms of energy utilization and waste.

Originality/Value: The study's scientific interest is to provide a framework to make the DT technology accessible, cost-effective, and scalable to logistics operations in SMEs.

Keywords: Digital Twin Technology, Logistics Optimisation, SMEs, Supply Chain Management, Predictive Analytics, IoT, Fleet Management, Real-time Data, Operational Efficiency, Data Integration, Cost Reduction, and Scalable Solutions.

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Key Abbreviations

SMEs - Small and Medium-sized Enterprises

DT - Digital Twin

ERP - Enterprise Resource Planning

WMS - Warehouse Management System

IoT - Internet of Things

KPI - Key Performance Indicator

AI - Artificial Intelligence

ML-Machine Learning

MQTT - Message Queuing Telemetry Transport

API - Application Programming Interface

PLC - Programmable Logic Controller

BOM - Bill of Materials

CPS - Cyber-Physical Systems

SCADA - Supervisory Control and Data Acquisition

BI - Business Intelligence

3D MCD - 3D Mechatronic Concept Design

OEM - Original Equipment Manufacturer

R&D - Research and Development

OPC- Open Platform Communications

UA- Unified Architecture

MES-Manufacturing Execution System

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1.0 Background and Introduction

Improvements in Digital Twin technology are shaking up companies and sectors around the globe. The use of logistics optimization in small and medium-sized enterprises (SMEs) within the manufacturing industry is receiving increasing attention (Iliuţă et al., 2024). With DT, virtual stand-ins of assets, systems, or processes enable real-time monitoring, prediction, and efficiency gains (Moiceanu & Paraschiv, 2022). Digital Twin particularly benefits logistics, where efficiency and cost reductions drive competitiveness.

1.1 Problem Gap

Although there is an increased global awareness of DT technology, the level of adoption and implementation is predominantly limited to large-scale corporations with vast financial and technical capabilities. The struggles of the SMEs that constitute the backbones of most manufacturing economies are the high cost of implementation, the absence of skilled labour, and the inability to integrate the DT with the other legacy systems. Much of the current and

commercial case studies concentrate on large companies and do not provide much guidance to the SMEs on practically using DT to optimise their logistics process in limited settings.

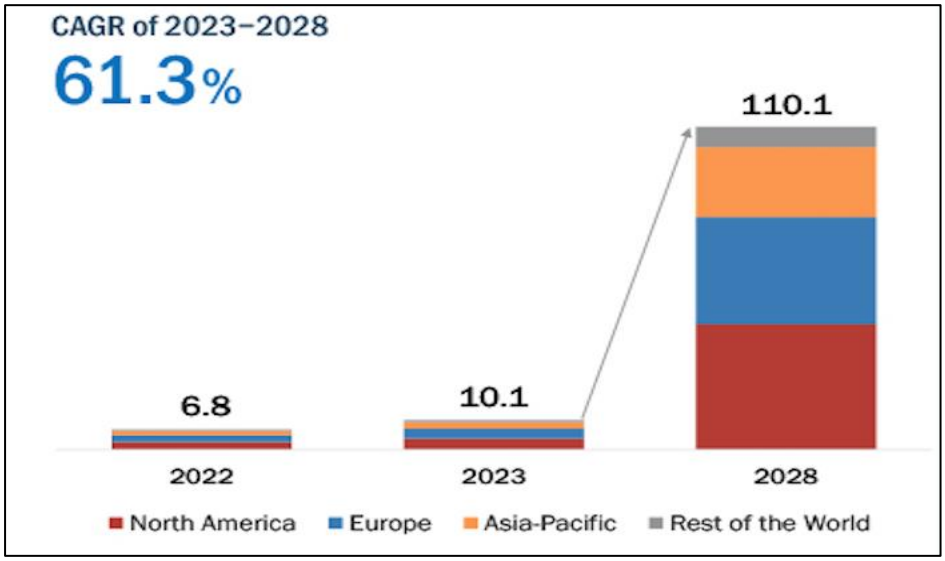
There is a lack of knowledge on particular strategies, tools, and step-by-step methods that SMEs can use to incorporate DT in a cost-efficient and scalable way. The proposed study fills this gap by offering a specific framework aided by the case studies of SMEs to direct DT's cost-effective and viable implementation within the logistics context.

1.2 The Evolution and Concept of DT Technology

In 2002, Dr. Michael Grieves brought DT technology to life in a research project about product lifecycle management (Kshetri, 2021). Before, the DT only stood for virtual models of materials or machines, but today, it also covers processes, systems, and even companies (Singh et al., 2021). The main idea of DT is to produce a virtual version of a physical object with updates, models, and forecasting tools. Because of this, businesses can check on how they operate, generate specific scenarios, expect outcomes, and streamline processes whenever needed (Javaid et al., 2023).

As indicated in Figure 1, global DT market projections show a high growth rate, with market size expected to reach $110.1 billion by 2028 (up from $10.1 billion in 2023; CAGR 61.3%) (MarketsandMarkets, 2023).

Figure 1: DT market size and projected growth rate



Note: Adapted from "Digital Twin Market Size, Share, and Trends" (MarketsandMarkets, 2023). Retrieved from https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html

Such significant growth in the market is a sign that more people are adopting DT in manufacturing, logistics, healthcare, and urban planning. With Digital Twin technology in logistics, users can make 3D models of transportation systems, warehousing, and inventory systems, and always watch over them for optimization.

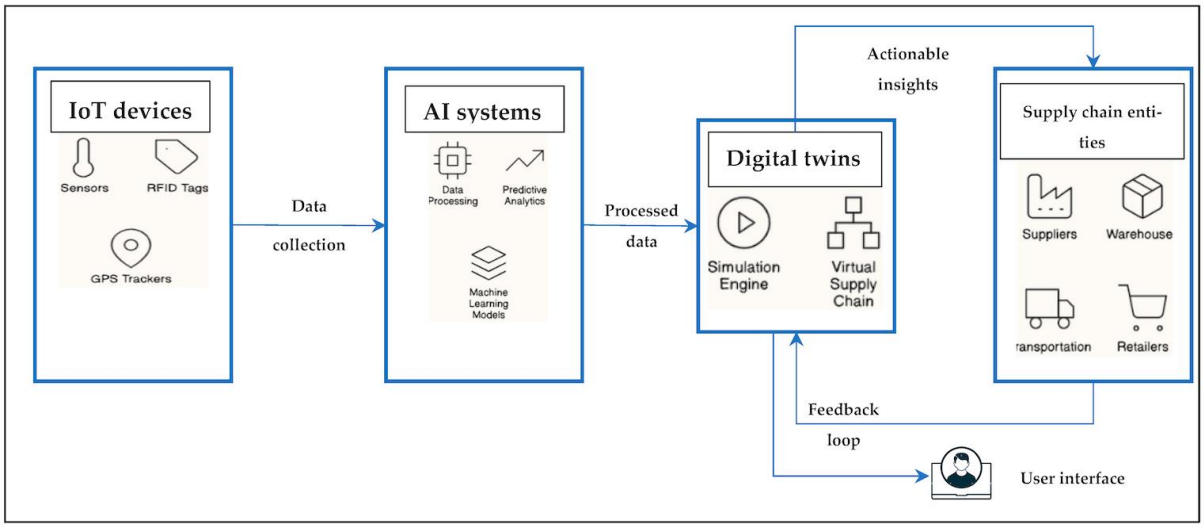
1.3 The Importance of Logistics Optimization in Manufacturing SMEs

SMEs form a significant share of the manufacturing sector worldwide. The U.S. Small Business Administration indicates that SMEs constitute 99.9 % of all the private businesses in the country, and their number of employees exceeds 47% of the private employment in the nation. (U.S. Small Business Administration, 2022). Even though there are many of these enterprises, many find it challenging to improve their logistics operations due to insufficient resources, old equipment, and a lack of access to the latest technologies.

Better logistics systems in manufacturing SMEs help smooth operations, save costs, and compete effectively (Keelson et al., 2024). Minimizing logistics costs, cutting down the time it takes to deliver, quicker inventory turnover, and better response to customers can all come from managing logistics efficiently (Oteri et al., 2023). Although logistics optimization is important, SMEs often struggle to set up optimized processes due to expensive software and manual planning (Costa et al., 2023). In this scenario, Digital Twin allows SMEs to manage their logistics operations cheaply by letting them test, modify, and study various options.

Creating computer models of physical logistics such as supply chains, transportation, inventory, and warehouses is the essence of DT in logistics (Liu et al., 2024). Figure 2 illustrates how digital models can be linked to sensor and IoT data to track goods, monitor transport routes, anticipate delays, and manage inventory (Roman et al., 2025).

Figure 1: *Elaboration of IoT and AI implications in digital twin applications*



Note: The diagram elaborates how the digital representations align with real-time data of sensors and IoT devices in following the status of goods, including involvement of transportation routes. Retrieved from "State of the Art of DT in improving the resilience of supply chains" by E.-A. Roman, A.-S. Stere, E. Roșca, A.-V. Radu, D. Codroiu, and I. Anamaria, 2025, Logistics, 9(1), 22 http://doi.org/10.3390/logistics9010022. Copyright 2025 by MDPI.

According to the research of Werbińska-Wojciechowska et al. (2024), DT is applicable in enhancing inventory maintenance and transport in logistics processes. An organization that receives real-time data is capable of practicing various logistical strategies, forecasting delays, discovering the most cost-efficient routes, and utilizing warehouses to maximum capacity. Such large volumes of information were previously only accessible to organizations that had huge budgets.

Digital Twin technology benefits logistics by enabling predictive maintenance (Nagy et al., 2025). For instance, one of the most typical cases of a transportation logistics organization implementing the digital twin technology in predictive maintenance is the Rolls-Royce Company and its TotalCare service. Rolls-Royce develops digital twins of jet engines to track real-time health data of a jet, which allows predictive analytics- analyzing sensor and

IoT data using AI and machine learning models, to predict with accuracy when certain maintenance is necessary before problems become critical. Carriers that avail this service conduct maintenance on a planned basis, and therefore, there are fewer unforeseen breakdowns and expensive unplanned groundings (Ojeda et al., 2025). Integrating AI and machine learning with DT in transportation logistics can increase logistics efficiency. AI algorithms can optimize warehouse layouts and delivery plans, while machine learning models can predict demand, adjust stock levels, and enhance customer service (Elbouzidi et al., 2023). The new tools help SMEs work better, spend less, and meet customer expectations.

1.4 Challenges and Barriers to Adoption in SMEs

Although DT offers numerous logistics advantages, SMEs face adoption barriers (Burinskienė & Nalivaikė, 2024). High upfront costs for models, sensors, and software remain difficult for smaller firms (Omowole et al., 2024). MarketsandMarkets (2023) reports relatively low SME adoption due to financial constraints. Small and medium-sized businesses must connect Digital Twin technology to their ongoing systems. SMEs often depend on old ways of handling logistics tasks, such as manual spreadsheets or outdated software. It is difficult for small organizations to successfully connect their legacy systems to advanced Digital Twins because they do not usually have the needed technical experts (Zhao et al., 2020). Since many SMEs cannot recruit qualified staff, this lack of technical knowledge is an excellent barrier to adoption. Besides, many people are still worried about the security and privacy of their data when dealing with DT technology. SMEs collecting massive amounts of sensor and IoT data should always set up safe storage and transmission for this information. Moving SMEs' Digital Twins to the cloud exposes them to cybersecurity threats. Benjamin et al. (2024) inform that many SMEs find it hard to implement DT technology due to the cost of security solutions.

1.5 Comparison with Large Enterprises

SME vs. Large Corporation Adoption of DT Technology The situation of SMEs adopting DT technology differs markedly from that of large corporations due to disparities in

resources, technical capacity, and strategy. Conversely, SMEs have under-strained budgets and generally lack specialised human resources to manage complicated digital change programs. This constraint precludes their ability to invest in far-reaching DT environments and often requires bite-sized or cloud-based implementation strategies. In addition, SMEs have to struggle to integrate DT with legacy systems and break workforce opposition due to training limitations. Furthermore, big companies tend to be favored more by the government and enjoy better access to consultancy services in their digital transformation than SMEs, where they have to venture into adoption with little or no external help. Notwithstanding these limitations, SMEs can use the DT technology by introducing focused, low-end solutions, especially on the logistics front where predictive upkeep, stock optimization, and real-time monitoring can show quantitative returns. Thus, although the opportunities brought by DT have massive implications on both PS, SMEs have a more prolonged, risk-averse adoption process based on long-term prioritization and alliance with technology vendors. This situation deficit explains why SME-oriented frameworks that consider restricted funds and stage implementation policies are crucial.

1.6 Opportunities for SMEs in Adopting DT Technology

Despite the challenges mentioned, SMEs will likely use digital twin tools to streamline logistics. Cloud-based solutions for DT allow SMEs to use the technology relatively inexpensively since they do not need to spend heavily upfront (GlobeNewswire, 2024). Businesses no longer need to pay upfront for Digital Twin technology using the cloud, so capital costs are vastly lowered. The rise of open-source Digital Twin frameworks and tools allows SMEs to build and use their logistics models digitally more easily. The fact that SMEs can customize these solutions removes some difficulties when entering the cloud market (Liu et al., 2023). Teaming with technology providers can help SMEs address their problems when beginning with Digital Twin adoption. SMEs can rely on partners to open the door to technical help, training, and essential resources they might not have otherwise (Peretz-Andersson et al.,

2024). Teamwork in SMEs allows them to address the risks of using Digital Twin solutions while getting the most significant benefits from this technology. Logistics optimization for manufacturing SMEs can be improved using Digital Twin, which offers live data, predictive functions, and simulation tools. SMEs might find it challenging to adopt cloud-based solutions since they may lose money during the first phase, lack skills, and face security issues. Still, alternative ways, such as open-source solutions and industry teams, are available. Logistics firms that use Digital Twin technology will find it easier to save money, work more efficiently, and compete on the world stage (Gennitsaris et al., 2023).

2.0 Research Questions, Aim and Objectives

2.1 Research Questions

The research will address the following key questions:

1. **RQ1**: How have manufacturing SMEs implemented DT technology in their logistics operations to optimize efficiency and reduce costs?
2. **RQ2**: What specific challenges have manufacturing SMEs faced in adopting DT technology for logistics, and how have they overcome these challenges?
3. **RQ3**: What measurable outcomes have manufacturing SMEs achieved through the implementation of DT technology in logistics?

2.2 Research Aim and Objectives

Table 1: Objectives and Research aim

Objective	Description	How the Research Aims to Address It
Objective 1: To evaluate the implementation of Digital Twins in logistics operations of manufacturing SMEs.	This objective aims to assess how DT technology has been integrated into the logistics operations of manufacturing SMEs, understanding the effectiveness of its application.	The research examines case studies, reviews industry reports, and explores existing implementations of Digital Twin technology in SMEs to understand the scope and impact of its use in logistics operations.
Objective 2: To determine the advantages and obstacles manufacturing SMEs experience when implementing Digital Twin technology to optimize logistics.	The aim of the study are to reveal the benefits and challenges SMEs experience when implementing Digital Twin technology into their logistical operations.	The study focuses on quantitative information of previous research, responses in the industry, and opinion surveys to establish the non-tangible value-adds and issues, and gives certain tangible specifics as to how SMEs are solving the issues.
Objective 3: To offer recommendations and plans of action that manufacturing SMEs can utilize to optimize their	The purpose of this objective is to elaborate on the use of the practical recommendations and approaches by supporting the	The study offers practical recommendations drawing on the results of case studies, expert surveys, and lessons learned to assist SMEs in

logistics-related operations with the help of Digital Twin technology effectively.	manufacturing SMEs to embrace and maximize the use of Digital Twin technology to bolster logistics performance.	embracing Digital Twin technology successfully and ensure maximum returns.

3.0 Literature Review

Manufacturing enterprises can now enhance their logistics thanks to the help of the DT technology (Cremonini et al., 2025; Rahmani et al., 2024). The review examines how SMEs have used DT, what problems they encountered, and the outcomes they could measure because of it. Up-to-date literature is studied to gather information, data, statistics, and case studies to show the pros and cons.

3.1 Implementation of DT Technology in Logistics Operations

The aspect that DT causes virtual representation of real objects, equipment, or systems has played a pivotal role in enhancing the logistics in manufacturing SMEs (Rahmani et al., 2024b). Yasin et al. (2021) inform that DT allows SMEs to simulate and supervise real-time logistics activities, boosting efficiency and cutting supply chain costs. Thanks to DT, small logistics

firms may monitor their stock 24/7, gauge demand in advance, and choose the best delivery routes using simulated feedback (Kim et al., 2025). Also, IoT and AI are among the technologies that assist in collecting data and forecasting information. Abideen et al. (2021) mention that SMEs using technology with AI-based forecasting decreased their operational costs by 18% in logistics. As a result, the companies could handle inventory better and avoid out-of-stock and overstock situations. To efficiently manage logistics, SMEs now rely on simulating and predicting possible supply chain problems (Alshahrani & Salam, 2022). After noting that DT enables SMEs to connect their production lines to logistics systems, Alshahrani & Salam (2022) state that, as a consequence, in this way, SMEs have better visibility of their supply chains. The fact that logistics operations can be easily altered allows SMEs to better react to an increased demand or other issues with the supply chain that would otherwise destabilize SMEs in fast-moving markets (Tukamuhabwa et al., 2021). Mayorov and Egorova (2024) remark that Digital Twin technology allows for significantly improving logistics flow, particularly in manufacturing settings. Through feed-forward continuous data processing and analysis, Digital Twin systems can help manufacturing SMEs better assess and model different aspects of logistic operations, including transportation, inventory, and warehouse. These virtual models can, therefore, mimic some real-life situations, evaluate various operating conditions, and demonstrate possible hazards and suboptimal situations. Adesola et al. (2025) observe that another practical aspect of DT is equally applicable in global supply chain optimization. Their study indicates that DT can reduce the operational cost by 30-40% and increase the time lag to supply chain disruption by up to 60%. The real-time monitoring and modeling provide the structure of DT with possibilities to be more productive, spend fewer resources, and attain superior supply chain consistency in various situations. Since DT systems operate in conjunction with IoT technology, real-time data streams are essential in swarming logistic environments; therefore, there is a need to develop DT systems (Homayouni et al., 2024). Using

DT in proactive prediction enables better management of risks and the overall improvement of supply chain risks.

3.2 Challenges in Adopting DT Technology for Logistics

While DT in logistics is helpful to manufacturing SMEs, it still brings some difficulties, mainly due to the lack of resources, issues with data, and complicated technology. Another big problem is getting the technology needed in the first place (Restrepo-Morales et al., 2024). As explained by Kang & Kim (2024), the considerable expense of purchasing hardware and software can make DT integration hard for SMEs. This point is critical, since implementing DT can be too expensive for many SMEs. Integrating old systems with new technologies from digital transformation is yet another serious issue. Rahmani et al. (2024) inform that many small companies continue to use old technology systems that cannot support modern digital technologies. Mismatching current with previous systems creates data silos and makes operations less effective, thereby stopping DT applications from achieving their full benefits (Wu et al., 2025). SMEs do not usually have the knowledgeable workforce to apply and manage advanced technologies, so it becomes even harder for them to use DT widely. The complexity of data integration also poses challenges. For DT technology to successfully improve logistics, its data should always be of high quality, coordinated, and recent (Dossou & Nshokano, 2023). SMEs encounter problems with data inconsistency and poor quality, reducing their chances of making the right decisions from digital technologies. Many SMEs are gradually implementing cloud-based digital transformation (DT) solutions, which cut costs and allow businesses to grow easily. As Abolghasem and Carpitella (2024) point out, cloud platforms allow SMEs to use DT technologies through subscription, which helps reduce the upfront costs and gives more choices in use (Abolghasem & Carpitella, 2024).

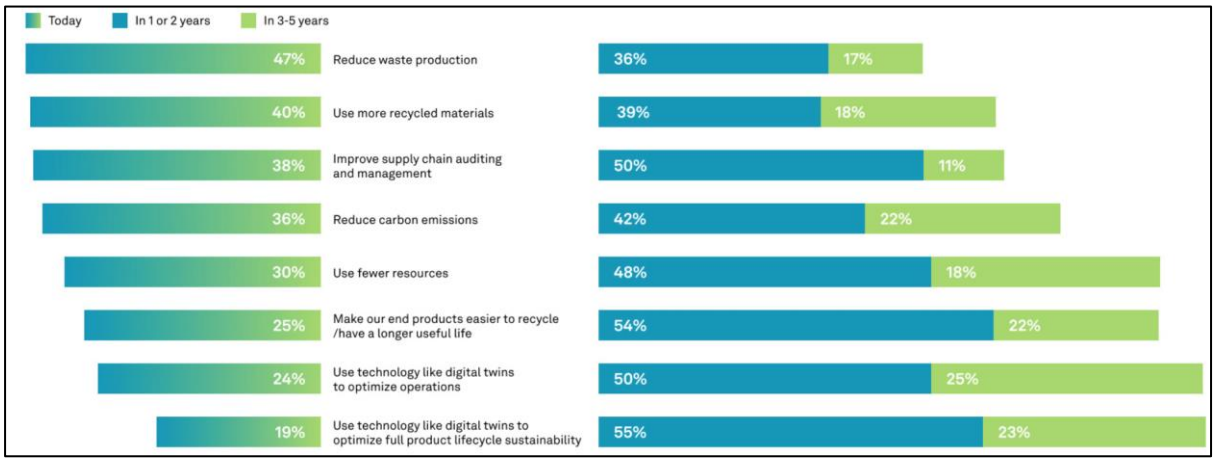
3.3 Measurable Outcomes from Implementing Digital Twin Technology

Manufacturers in the sector have achieved various measurable and visible achievements after using DT technology in logistics. An important advantage is that it helps businesses lower

their daily costs. "Integrating Digital Twin (DT) technology into logistics systems at SMEs can lead to a 15% reduction in transportation costs by enabling more efficient route optimization and better fleet management (Krishnan et al., 2024)". Fuel usage is minimised by simulating transport conditions and updating routes in real-time, as well as improving on-time delivery. The other significant advantage of implementing Digital Twin (DT) tech in the logistics industry is improved inventory management. Ramingwong et al. (2024) reveal that companies that utilize DT in improving their logistics have an increased rate of stock turnover. The tools allow companies to precisely predict demand and enable delivery of the correct products at the correct time to reduce the danger of a stock out or overstocking. This provides massive cost savings and cost effectiveness. Customer satisfaction has also grown due to digitization Twin (DT) technology. SMEs can shorten delivery times by using DT and better respond to consumer needs, thereby improving the quality of their services (Sharabati et al., 2024). More efficient logistics also makes the customers happy, which is a key issue for SMEs pursuing a competitive edge. On top of that, DT aids in sustainability programs. Kannan and Gambetta (2025) also claim that SMEs can optimize the use of their resources, lessen waste, and minimize harm to the environment with the help of virtual simulations made possible by DT. In general, DT has become an effective facilitator of operational excellence that enables organizational cost reduction and efficiency. Kharchenko et al. (2020) claim that DT systems also positively influence supply chain management, as these systems make it possible to detect and determine excess inventory, thereby ensuring streamlined operations and customer satisfaction." Adesola et al. (2025) list that the SMEs mentioned earlier who implemented DT technology benefited from the reliable supply chain. The flexibility to foresee these disruptions and manage such risks enabled SMEs to minimize disruptions and their impacts. Decision support through DT systems helped improve the decision-making capacity of SMEs; resources and logistics activities that were complicated and time-consuming became more manageable. Another benefit of integrating Digital Twin technology is enhancing forecasting and demand planning

levels. Mayorov & Egorova (2024) indicate that Digital Twin offers promising analytical capabilities that help manufacturing SMEs anticipate demand more proficiently, eliminating prevailing stockout and overstock situations. This is especially true for SMEs under pressure to offer their commodities cheaply while focusing on efficient stock management.

Figure 2*:* Global manufacturing technology decision-makers on digital twin adoption



Note: Retrieved from a study commissioned by Hexagon and carried out by Forrester Consulting in May 2023. https://hexagon.com/resources/insights/digital-twin/statistics

In recognition of its rising stature, DT's global market size will rise to 240 billion EUR in 2032 with a CAGR of 39.8% within the forecasted period (Fortune Business Insights, 2024). About 29 percent of the manufacturing companies across the globe have already implemented activities of DT in their entirety or partially, 65 percent of manufacturers are applying them to streamline their operations and 67 percent of the manufacture technology decision-makers will be busy concentrating on the application of DT to attain full sustainability of their products lifecycle (Forrester Consulting, 2023). These statistics indicate the opportunities DT technology is bringing in terms of the radical possibilities of transforming production processes, enhancing efficiency, and reducing costs, as well as making operations more resource-efficient.

3.4 Future Directions for DT Technology in Logistics Optimization

The future of DT in logistics will include using AI, ML, and blockchain more widely in daily operations (Mousavi et al., 2024). Because of these technologies, DT can make better decisions, as systems can simulate logistics and change and improve processes independently (Zaidi et al., 2024). As SMEs move toward "autonomous logistics," they will depend less on people, make fewer mistakes, and enhance their operations.

Adopting blockchain will increase transparency and security in logistics. Blockchain securely stores logistics data, enabling all supply chain people to work with accurate and up-to-date information (Karaduman & Gülhas, 2025). Combining DT and blockchain will help SMEs make their logistics operations more reliable.

The use of 5G will strengthen DT technology. Large-scale data processing on 5G networks will lead to more flexible and prompt logistics actions. Using 5G, AI, and DT, SMEs can respond swiftly to disruptions and make data-backed decisions.

SMEs in manufacturing have found that the logistics process has drastically improved with the use of DT. Performing real-time data collection, superior predictions, and simulated processes makes SMEs pay less, work more efficiently, and deliver to their customers happily. Even so, difficulties linked to the cost of getting started, combining information, and having skilled workers must be managed to take full advantage of DT. Digital twins in logistics will continue to benefit SMEs when technology advances due to further developments in AI, machine learning, and blockchain.

3.5 Criticism of the Gaps in the Existing Literature

Despite the existing body of literature on the potential of the Digital Twin (DT) technology to revolutionize logistics and manufacturing, most studies are relevant to large organizations with high digital readiness and huge finances. Existing research on SMEs continues to be limited, especially concerning the practical application of DT solutions in SMEs with unique limitations, including limited budgetary capacities, availability of legacy systems, and limited methods of technical expertise.

Moreover, most available research is theoretical and/or explorative. Longitudinal and implementation-oriented studies are nonexistent, but they can provide a picture of practical outcomes in SMEs. Also, a few directions are present on cost-effective and phased adoption walk, measurement of return on investments (ROI), and the acquisition of workforce skills necessary to utilize DT tools to maximum effect.

Second, although specific sources mention the advantages of sustainability, there is no in-depth research on the ecological consequences of the DT used by SMEs.

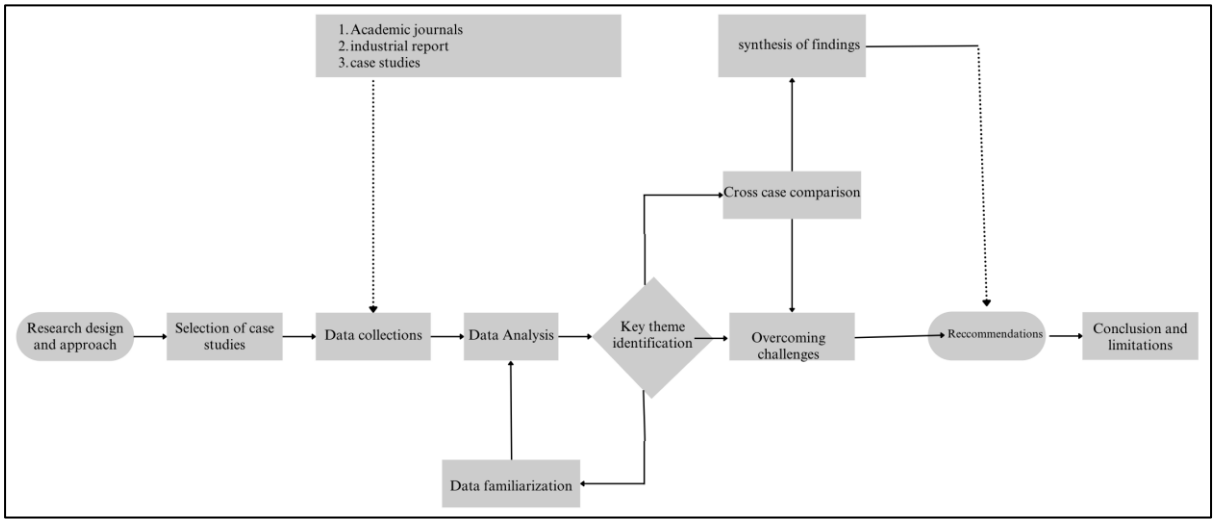
This paper would fill these gaps since it combines the review of a case experience, applies the appropriate frameworks, and provides workable, feasible recommendations on how to facilitate logistical operations in SMEs.

4.0 Methodology

This study proposes a case study by exploring the usage of Digital Twin technology in logistic processes of manufacturing SMEs (Loaiza & Cloutier, 2022). The research aims to determine how DT can streamline the supply chain logistics and reduce costs.

The choice of the case study approach seeks the possibility of obtaining more comprehensive knowledge about the peculiarities of the challenges and opportunities faced by utilizing SMEs' DT solutions (Baxter & Jack, 2016). Secondary data collection is applied in the research study to attain detailed information about the implementation of DT, as defined in the research proposal, and the implications of the DT on the SMEs.

Figure 3*:* The Research methodology framework



Note: Author's elaboration of research methodology framework for this study.

4.1 Research Design and Approach

The case study methodology was adopted, which helps focus on real-life settings when the topic is fresh or little explored. Examining different case studies using the methodology provides insight into using DT and the issues encountered by SMEs using it in the logistics

sector (Crowe, 2017). This study explores the topic of DT technology in SME logistics operations. The research technique uncovers useful information about using Digital Twin, the difficulties SMEs encounter, and the achievements it leads to (Saka et al., 2023). This study will use case studies as its focus and thus analyze pre-existing secondary sources such as academic articles, industry reports, and documented examples of Digital Twin's success in manufacturing SMEs.

The choice of the qualitative research approach is because this work is devoted to the study of introducing Digital Twin (DT) technology into the operation of SMEs within the framework of the current organizational structure and resource capabilities. Unlike quantitative research, which functions within numerical information and statistical modeling, qualitative research allows a better understanding of real-life situations. It will look at organizations' troubles, decision-making, and complexities in the implementation practices of Digital Twin (DT) solutions.

This method examines the critical but arguably less quantifiable and more case-dependent characteristics, including organizational preparedness, employee flexibility, and integration complexities, through case studies and readings of documented industry reports. Since the large-scale data on DT adoption among SMEs is scarce, an approach based on qualitative methodology is the most suitable to identify effective strategies, fill the gap in implementation, and develop a practical framework that would reflect the situations of real-world operations of SMEs.

4.2 Selection of Case Studies

The case study review method was employed to understand further how manufacturing SMEs can adopt Digital Twin (DT) technology in logistics. To ensure that each organization

has been able to optimize its logistics operations by implementing DT solutions, the cases selected had to meet particular inclusion criteria."

Table 2: Case studies Selecting Criteria

Selection Criteria	**Keywords**	**Inclusion Criteria**	**Exclusion Criteria**
Industry Relevance	Manufacturing, Logistics, Sectors	Case studies from diverse manufacturing sectors (consumer goods, automotive, electronics)	Cases from non-manufacturing or irrelevant sectors
Documented Use of Digital Twin	Implementation, Documentation, Technology	SMEs with documented use of Digital Twin in logistics (reports, case studies, data)	Lack of documented implementation or unclear use of DT
Geographical and Sectoral Diversity	Regions, Cross-sectoral, Global	Case studies from SMEs in varied geographical locations	Cases limited to one geographic region or sector
Size of SMEs	Small, Medium, Employees (1-250)	SMEs with 1-250 employees in logistics-focused operations	Enterprises outside the SME size range (less than one or more than 250 employees)

4.2.1 Industry Relevance

The chosen case studies must be from manufacturing SMEs in industries that heavily depend on logistics. These may include sectors such as manufacturing, automotive, food preparation, electronics, and weaving fiber into textiles (Banerjee, 2018). As a result, the research collects various cases where the Digital Twin is applied.

4.2.2 Documented Use of DT Technology

The case studies include the SMEs that have expressed their use of DT in logistics. The documentation might consist of reports prepared by the company, case studies made public, or technology providers' data showing the process and the achievements. Using well-documented cases, the research achieves a strong level of validity and accuracy.

4.2.3 Geographical and Sectoral Diversity

The studies included come from companies located across various regions to enhance how far the study can be applied. As a result, it becomes easier to see the variations in Digital Twin use based on what happens in different regions and sectors.

4.2.4 Size of SMEs

Most SMEs have employees ranging from 1 to 250 (Millers & Gaile-Sarkane, 2021). This research will study SMEs because different challenges and opportunities are common depending on the company's size.

4.3 Data Collection

Because the research only uses secondary data, data collection involves finding information from numerous reliable and appropriate sources. Secondary data comprises industry studies, articles from academic magazines, and open-access case studies. The purpose is to work with solid, recognizable data to fill the gaps found in the existing research. The data collection process includes the following steps:

4.3.1 Review of Academic Journal Articles

Academic journals found in articles are thoroughly analyzed. The articles considered concern a study regarding the application of DT to industrial and logistics companies, particularly SMEs. They discuss the theory and practice businesses use, list the expected benefits and challenges of applying the technology, and detail real outcomes SMEs report. Relevant academic articles on JSTOR, ScienceDirect, and Google Scholar ensure the Research includes recent studies. Preference will be given to articles around the use of DT in SMEs' supply chains and logistics, as they will inform the Research.

4.3.2 Industry Reports and White Papers

Top-level consulting companies like MarketsandMarkets publish reports to assess market size and growth rate. These documents usually give helpful information about trends, insights, and benchmarks for using Digital Twin technology. Such reports will be critical because they include information on the quantitative and qualitative ways SMEs in logistics use Digital Twins. The reports will provide more details on the results from the case studies and highlight essential changes within the industry.

4.3.3 Case Studies from Industry and Technology Providers

The data gathered will also contain case studies shared by technology providers such as Siemens, IBM, and GE Digital. These case studies explain how DT is used in logistics, giving examples of the problems, methods, and outcomes observed in SMEs. Case studies that technology vendors include in their marketing or white papers can provide valuable information beyond academics. Case studies are to provide insights into project execution, the type of technology used, and the results they brought.

4.3.4 Publicly Available Data from SMEs

Reviewing reports, white papers, or news stories shared by others about SME use of Digital Twin will also be helpful. These documents are from industry organizations' websites, business publications, or collections of business cases. These sources show how SMEs in different areas have introduced DT technology to their supply chain management.

4.4 Data Analysis

This Research uses qualitative methods to analyze information from the collected case studies and secondary sources. Thematic analysis is a widely used technique to identify and interpret any themes present in the qualitative data, and it will be applied to pick them out and make sense of them (Caulfield, 2019).

4.4.1 Familiarization with the Data

First, the writer responsible will analyse all sources collected, including scholarly literature, case reports, industry news, and official data on SMEs, to ensure a good knowledge of the content before commencing with the code. In this phase, the writer will select irrelevant and excessive information and determine whether there are best practices and recommended roadmaps for implementing such ventures.

4.4.2 Identification of Key Themes

After data coding, it is time to broadly organize similar codes into thematic groups. The main themes in this study will be the process of deployment, technological and cost-related issues, and the results of adopting the Digital Twin technology. These themes align with the research questions to accomplish their objectives.

4.4.3 Cross-Case Comparison

The study will compare the use of the Digital Twin technology in logistics in unrelated companies through a cross-case analysis. The results of each case study will be presented and compared to one another to find common patterns, similar aspects, and individual peculiarities. Such a comparison will point out similar characteristics and practices peculiar to a specific industry or region of SMEs using Digital Twins.

Table 2*:* Potential Biases and Mitigation Strategies in the Research

Type of Bias	Description	Mitigation Strategy
Selection Bias	Case studies selected may not fully represent all SME sectors or regions.	Included diverse SMEs across industries and geographies; applied defined inclusion criteria (see Table 2).
Publication Bias	Over-reliance on successful or well-documented cases might skew findings.	Incorporated positive and negative case outcomes; used multiple sources, not only vendor reports.
Researcher Interpretation Bias	Personal assumptions may influence how qualitative themes are coded and interpreted.	Used thematic analysis with peer-reviewed frameworks; ensured cross-case comparisons to validate patterns.
Confirmation Bias	Tendency to focus on evidence that supports the expected benefits of DT.	Actively sought contradictory findings; included challenges, failures, and limitations of DT adoption.
Data Availability Bias	Limited access to primary SME data may affect comprehensiveness.	Supplemented with secondary data from white papers, government reports, and academic literature.

5.0 Data Collection and Analysis to Address Research Questions

The framework of the synthesis of results incorporates the findings into the recommendations of the small business interested in using the DT technology in its logistics (Noyes et al., 2020). The recommendations show how to apply DT technology in logistics systems, following the cases where it has worked. Provide the methods of overcoming such barriers to the use of DT, such as high cost, complex technologies, and problems with data integration. The research will make SMEs comprehend how to organise logistics operations to be effective, reduce expenditures, and increase the ROI using DT, with a results summary. The research utilizes primary sources of information, including academic articles, industry reports, and case studies, to examine the questions and implications of DT usage in logistics. The study results will add to the existing knowledge in the study area and offer specific recommendations that SMEs should use when managing their logistics.

5.1 Technology Adoption by Canadian SMEs

Table 4 highlights the differences in adopting advanced and emerging technologies between women-owned and men-owned businesses. The results show that:

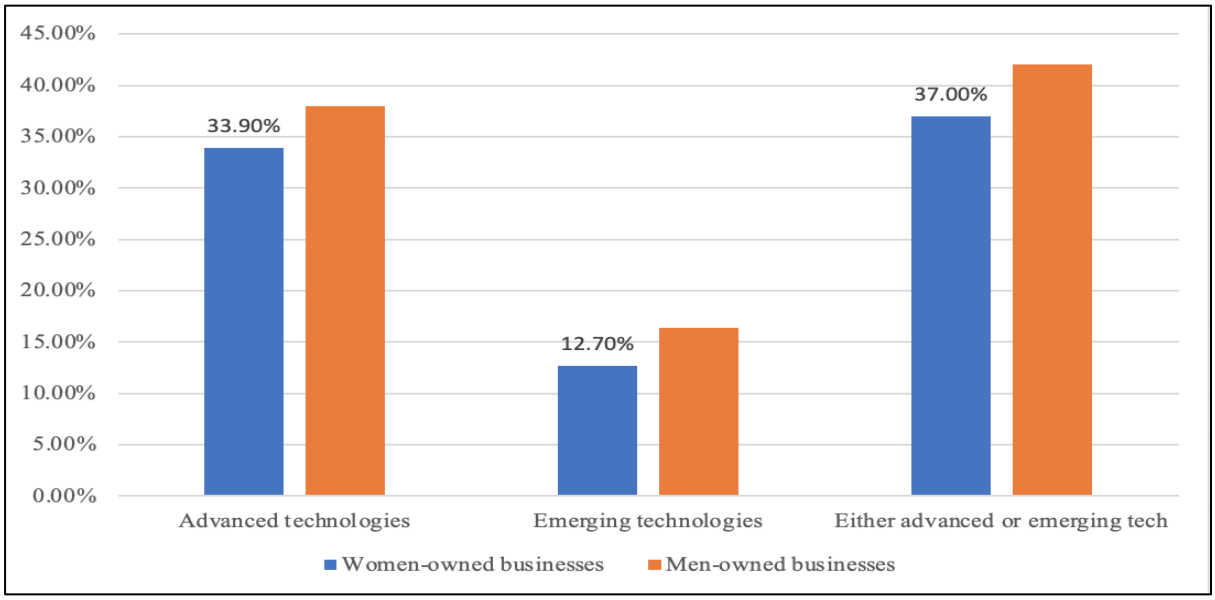
Table 3: *Use of Technologies by Ownership Type*

Technology Type	**Businesses owned by Women**	**Businessses owned by Men**	**P-value**
Advanced technologies	33.9%	38.0%	0.141
Emerging technologies	12.7%	16.4%	0.077
Either advanced or emerging tech	37.0%	42.0%	0.077

In Table 4 above, the differences in the pattern of technology adoption among Canadian SMEs in ownership type were significant in adopting emerging technologies, indicating that women-owned businesses lagged behind those owned by their male counterparts. Women's businesses are nearly as likely as those owned by men to use advanced technologies, like logistics and

supply chain management tools, but less likely to use emerging technologies like DT systems. The data suggest that financial constraints, limited technical knowledge, and challenges in accessing training may contribute to these disparities.

Figure 4: *Use of Technologies by Ownership Type*



Note: The above graph shows the technology adoption by Canadian SMEs owned by men and women. The data used was retrieved from Statistics Canada: https://www150.statcan.gc.ca/n1/pub/36-28-0001/2024008/article/00003-eng.htm

Advanced Technologies: Women-owned businesses use advanced technologies like logistics and supply chain management tools at a lower rate (33.9%) than their male counterparts (38.0%), though the difference is statistically insignificant.

Emerging Technologies: Businesses owned by women are remarkably lower in usage of emerging technologies (12.7%) compared to those owned by men (16.4%), with a significant difference at the 10% level (p-value = 0.077).

The overall trend suggests that Women-owned businesses are slower to adopt emerging technologies than those owned by men, which could be due to financial constraints, lack of technical knowledge, or difficulty accessing training.

These results suggest that while businesses owned by women are equally likely to adopt advanced technologies, they face more significant challenges in adopting newer technologies, which could include technologies like DT systems (Liu & Faryaar, 2024). These barriers are more pronounced in small to medium-sized businesses that struggle with resource allocation, access to funding, and talent acquisition. Filling these gaps can enhance the adoption rate of advanced technologies and rising technologies such as DT in women-owned businesses.

5.1.1 Use of Emerging Technologies by Subcategory and Ownership Type

Table 5 presents the adoption of specific emerging technologies, focusing on technologies like AI, closely related to Digital Twin systems. The table shows the following data:

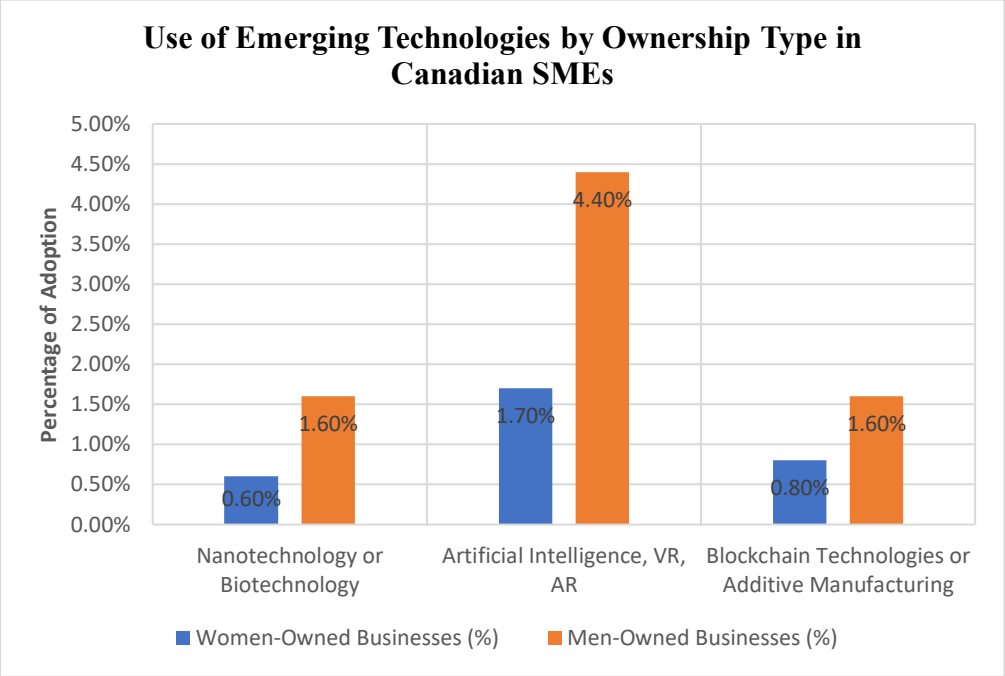
Table 4*: Use of Emerging Technologies by Subcategory and Ownership Type*

Type of Emerging Technology	**Businesses owned by Women**	**Businesses owned by Men**	**P-value**
Nanotechnology or biotechnology	0.6%	1.6%	0.003
AI, VR, AR	1.7%	4.4%	0.000
Blockchain technologies or additive manufacturing	0.8%	1.6%	0.012

As Table 5 above shows, there are significant gaps in the favourability of specific fastest-growing technologies like AI, nanotechnology, and blockchain use by Businesses owned by Women and those owned by men. The most striking difference is AI adoption, where women-owned businesses (1.7%) lag behind men-owned businesses (4.4%), with a statistically significant p-value of 0.000. Since AI is a core component of DT technology, this gap signals a considerable challenge for women-owned businesses in adopting such technologies. The lower adoption rates of other emerging technologies, including nanotechnology (0.6% vs.

1.6%) and blockchain (0.8% vs. 1.6%), further emphasize the difficulties women-owned businesses face in embracing advanced technologies.

Figure 5*: Use of Emerging Technologies by Subcategory and Ownership Type in the Canadian SMEs*



Note: The above graph shows the adoption of upcoming technologies by Subcategory and Ownership Type. Retrieved from Statistics Canada: https://www150.statcan.gc.ca/n1/pub/36-28-0001/2024008/article/00003-eng.htm

Artificial Intelligence (AI): The disparity between the rate of adoption of AI between women-owned businesses (1.7%) and men-owned businesses (4.4%) is statistically significant (P-value = 0.000). AI is a core component of Digital Twin technology, and its lower adoption rate among women-owned businesses signals a potential barrier to adopting DT systems.

Nanotechnology and Biotechnology: There is also a significant disparity in these technologies, whereby businesses owned by women (0.6%) are less likely to utilize them than those owned by men(1.6%), whose p-value is 0.003. Blockchain: The share of women-owned businesses that have some adoption of blockchain (which includes limited and no adoption) is lower than that of men-owned businesses, 0.8 percent versus 1.6 percent, which is a statistically significant difference at the 5 percent level of significance (p-value = 0.012). This information proves that

women-owned businesses are more burdened with challenges to embrace technologies that are the key to DT systems, including AI and blockchain. This discrepancy may be due to many factors, including finances, training access, and inexperience in using high-tech tools. According to Statistics Canada, female-owned businesses in Canada are about ten times less prone to use any emerging technology.

AI, compared to their male-owned businesses (Liu & Faryaar, 2024). Since AI is a critical part of the DT technology, it poses a significant difficulty for female-owned companies when embracing such technologies. The stumbling blocks are multidimensional and entail financial constraints, inability to access knowledge on technology, and the process of training or upskilling the workforce. With the introduction of DT technology, SMEs working in a manufacturing environment can streamline logistics. DT systems also include real-time tracing and mining of performance data and scenario planning, which can improve decision-making and aim to use more resources, reduce expenses, and enhance the flexibility of the supply chain.

However, integration complexities, data quality, and a skilled workforce are some of the barriers that have been put in place to derail the successful implementation of this technology. These gender-based differences in the adoption of the emerging technologies, especially the much lower adoption levels of AI and blockchain among women-owned SMEs, have implications for Digital Twin implementation strategies. Digital Twin systems are based on AI and IoT technologies, meaning women-owned SMEs might face even more obstacles when adopting DT. It constitutes less availability of high-tech digital infrastructure, less investment in digital innovation, and fewer chances of raising workforce digital skills. Thus, DT implementation policies must consider these system gaps to provide more extensive access to technical assistance, specific grant programs, and education programs. Equity should be at the forefront of public or private stakeholders who want to nurture the integration of DT amongst the SMEs, including providing special resources to women-driven firms, like mentorship programs, gender-inclusive pilot grants, and gender-friendly tech training. Filling

these gaps will make it more equitable and yield Digital Twin systems' highest economic and operational returns within the SME community.

5.2 Addressing Research Questions

RQ1: How have manufacturing SMEs implemented Digital Twin technology in their logistics operations to optimize efficiency and reduce costs?

Due to DT, logistics management for SME factories is now more straightforward and economical. The technology allows SMEs to establish virtual replicas of their property, procedure, or system so that all business oversight, analytics, and choices can be in real-time. Regarding logistics, the technology used to make the supply chain more transparent, eliminate the likelihood of downtime, better handle inventories, and enhance transportation efficiencies. Through analyzing the papers, the author finds out how small manufacturing firms have used DT technology for logistics and the positive results they have witnessed. Below are some key implementations observed in manufacturing SMEs.

Inventory and Warehouse Management

Manufacturing SMEs now use DT technology to help them run their warehouses more efficiently. Using RFID sensors and IoT, these companies can instantly monitor their stock, reducing mistakes and the costs associated with manual tasks (Mashayekhy et al., 2022). Moreover, this application utilizes the space architecture of warehouses better by enabling one to make decisions regarding the movement of goods through the assistance of zoning with data. It is worth mentioning the recent study by Mousavi et al. (2024), which examined a case of how a company associated with the automotive business digitalized its warehouse with the help of DT. Through this, they could automate their process of carrying out the replenishment of their inventory, prevent errors that occur in the store, obtain more storage room, and waste less money on the operation.

Supply Chain Visibility and Real-Time Data Integration

Due to DT, SMEs can create more transparency within their supply chain and coordinate real-time data in various process sections. DT makes it easy for SMEs to predict, expect, and manage goods easily when there is any disturbance in the supply chain. Case-based evidence presented by Dyck et al. (2023) demonstrates that a small or medium-sized enterprise dealing with textile manufacturing has created a digital replica of its end-to-end supply chain using DT. Due to such integration, they could examine how materials are moving in real time and decide how to allocate them and from whom to source them. Predictive Maintenance for Logistics Equipment.

Predictive Maintenance for Logistics Equipment

Businesses often prepare for the upkeep of forklifts, conveyors, or trucks by utilizing DT technology in logistics. Through predictive maintenance assisted by DT, SMEs do not pay much for unexpected repairs, stay working longer, and enjoy their equipment for longer. An SME in food manufacturing used DT to keep track of delivery trucks and could anticipate possible breakdowns in major parts like brakes and tires before they happened (Achouch et al., 2022). Doing this kind of maintenance in advance prevents most unexpected stoppages.

Transportation and Route Optimization

Companies in the SME sector have started using DTs for better transportation. Manufacturers use technology to check traffic conditions, fuel costs, and possible delays to find the ideal transportation route. It lets the companies choose the most cost-saving and time-saving roads, reducing fuel costs and delivery time. SMEs from the electronics manufacturing field applied DT to imagine several transport routes. By starting to use real-

time news and GPS maps, they reduced fuel usage by about 20% and made deliveries timelier by about 15%.

Table 5*: Industry examples added to strengthen linkage to literature*

Technology Application	**Industry**	**Implemented Technology**	**Outcome**
Inventory & Warehouse Optimization	Automotive	RFID, IoT-enabled warehouse management	Automated stock replenishment, optimized storage
Supply Chain Visibility	Textile	Digital twin of entire supply chain with real-time data	Improved tracking, faster decision-making
Predictive Maintenance	Food Manufacturing	IoT sensors, predictive maintenance system for trucks	Reduced downtime, proactive maintenance
Transportation & Route Optimization	Electronics Manufacturing	GPS integration, traffic analysis	Reduced fuel costs, faster deliveries

The above table summarizes how manufacturing SMEs can use DT technology to conduct logistics. The logistics branch of manufacturing SMEs has also utilized the DT technology to correct warehouse management, transportation costs, and time depreciation (Moshood et al., 2021). The technologies have assisted SMEs in streamlining their logistics, which has lowered their costs and resulted in greater efficiency in their operations.

SMEs in different manufacturing sectors have applied DT technology, which builds virtual copies of physical systems, to streamline logistics activities. The combination of the digital representations enables SMEs to track, model, and optimize real-time processes, resulting in a

more efficient, cost-effective operation. We now consider the application of Digital Twin technology as practiced by the industries in SMEs production in logistics.

Ornamental Stone Industry - Integration of Workforce Training and Operational Efficiency

The DT technology used by SMEs in the Portuguese ornamental stone sector was advanced simulation systems to train the workforce and optimize operations (Cremonini et al., 2025). These businesses have incorporated StoneCUT@Line, a state-of-the-art precision cutting system for ornamental stones, showing a detailed digital twin of the equipment.

DT implementation:

The StoneCUT@Line system developed a 3D model mimicking the actual problems of the gauge cuts (Cremonini et al., 2025). This digital equipment model was used to support predictive maintenance and live observation. It was the opportunity to streamline the cutting processes, reduce energy used, and waste materials by integrating this system (Cremonini et al., 2025). The SME was capable of operational efficiency by reducing downtime and enhancing the operator's training process, thus limiting the length of the process and embarking on training skills.

Cost Reduction

With the help of the DT of the system, the ornamental stone industry's real-time performance data was recorded, and the machines' workforce and schedule were accurate, which not only increased productivity but also aided in cost reduction because one could avoid using unnecessary machines, thus avoiding repair and loss of time.

Servo Motor and PLC Integration for Logistics Operations in SMEs

The SME used DT technology to track the state and rotation of servo motors in a logistics system, in the specific case of temperature-regulated environments. It began with the combination of the WAGO PLC (Programmable Logic Controller) with 3D experience

software that produced a Digital Twin that monitored the rotational movement of the servo motor under a temperature-controlled setting (Rahmani et al., 2024).

Digital Twin:

The system applied temperature data information from RTD sensors to establish a digital twin that simulated the behavior of the servo motor. It generated a direct virtual representation of the physical system. With links of the DT to the clouds, SMEs could have a repetitive check on the working conditions and real-time corrective measures to the system to make it effective.

Optimization and Cost Reduction:

With real-time data of the servo motor's DT, SME could prevent motor overuse and use it only when needed (Achouch et al., 2022). It assisted in saving energy and operational costs. Applications such as Grafana provide a form of data visualization that allows one to make superior decisions and instant variation of the system, thereby providing efficiency in the logistics procedures.

Key Benefits and Improvements Achieved Energy Efficiency:

Digital Twin technology also assisted the SMEs in Energy Efficiency, in the two scenarios, whereby the costs decreased through the implementation of Energy Efficiency in companies. Using the machines and systems more optimally, thanks to a more optimized scheduling that reduced energy waste.

Predictive Maintenance:

With the real-time tracking offered by the DT, SMEs would be able to keep the failing equipment at bay before it fails, thus experiencing fewer breakdowns and less downtime, in turn increasing the overall efficiency of the system (Abolghasem et al., 2025).

Skill Development and Training

The Digital Twin helped the ornamental stone industry streamline the workforce training process because operators could experience engaging, interactive machinery simulations

(Yasin et al., 2021). It made them quicker to become proficient, saving on operational and learning curves.

RQ2: **What particular obstacles have been encountered by manufacturing SMEs through the implementation of Digital Twin technology in the domain of logistics, and what have been the ways of surmounting them?**

Integration with Legacy Systems

Another significant issue is integrating DT technology into current logistics management systems. Some of these SMEs operate on legacy systems that may be unable to integrate advanced digital technologies (such as DT), making integration a complex and expensive process. Mousavi et al. (2024) show that cooperation between SMEs can remove the challenge of multiple IoTs from various vendors with a specific system integrator to facilitate the integration process seamlessly. In addition to middleware solutions such as Eclipse BaSyx, some SMEs have adopted middleware solutions that allow them to connect their disparate systems without modifying their existing systems too much.

Lack of Technical Expertise

The implication is that many SMEs cannot accomplish such functions in vital fields, such as utilizing information, machine learning, and IoT in-house. A Digital Twin system needs to be successfully implemented and run based on specific knowledge that SMEs lack. Dyck et al. (2023) add that SMEs have responded to this challenge by collaborating with technology providers, universities, and consultants for technical support and training. In other cases, SMEs have also chosen user-friendly DT platforms that do not demand much technical expertise.

Data Security and Privacy Concerns

The constant stream of IoT devices and the real-time data they provide present security and privacy concerns for these devices. For example, SMEs are very concerned about protecting sensitive data in food production and pharmaceuticals. SMEs overcome these fears through cloud-based platforms that apply encryption and high-level cybersecurity measures. Huang et

al. (2024) also stated that various companies are cooperating with those with expertise in cybersecurity to ensure that their method of data storage and data transfer are secure and comply with stringent security requirements.

Resistance to Change within the Organization

Another barrier identified is organizational resistance to adopting new technologies, a problem many SMEs are experiencing. It is apparent why employees may also turn their back on Digital Twin technology, fearing being out of a job or that it is too complicated. Change management strategies, such as employees' early involvement in adoption and clear communication regarding the DT technology, will be important for resolving the resistance.

Table 6*: Summary of Adoption Challenges, impacts and solutions*

Challenge	**Impact**	**Solution**
High Initial Investment	High upfront cost for infrastructure	Adoption of cloud-based or SaaS solutions to reduce initial costs
Integration with Legacy Systems	Difficulty in integrating with old systems	Use of middleware and specialized system integrators for smoother transitions
Lack of Technical Expertise	Lack of in-house knowledge	Partnerships with technology providers and universities for expertise and training
Data Security Concerns	Risks in data transmission and storage	Adoption of secure cloud platforms with encryption and working with cybersecurity experts
Resistance to Change	Employee reluctance to adopt DTs	Change management strategies and training programs to ease the transition

Adopting Digital Twin technology in logistics has many challenges, which however the SMEs have learnt some strategies to curb those challenges. SMEs have successfully implemented the DT technology in their logistics processes by using cloud solutions,

collaborating with system integrators, investing in education and enhancing the security of the existing data (Cremonini et al., 2025).

RQ3: What measurable outcomes have manufacturing SMEs achieved through the implementation of Digital Twin technology in logistics?

Implementing DT in logistics has allowed manufacturing SMEs to achieve several real results. In most situations, such outcomes strive to reduce the costs, enhance productivity, and make things more transparent, which certifies the actual benefits of DT in logistics practices. This section examines the impacts SMEs observe in applying DT technology in their logistics and supply chain undertakings.

Reduction in Operational Costs

Among the primary positive outcomes of implementing DT technology is sharper expense reduction regarding daily activities. SMEs have saved logistics costs by optimizing their inventory, better viewing their supply chain, and improving maintenance. Kaya et al. (2025) explain how adopting predictive maintenance guided by Digital Twin technology cuts maintenance costs for an SME in the petrochemical field. Unintended downtime was prevented by identifying problems, saving the company from repair charges.

Improvement in Delivery Times and Supply Chain Transparency

With the help of technology, the logistics companies have increased the speed at which delivery is made through updated routes and tracking. Decision-making is also faster and brings about less delay, as a direct result of increased transparency. According to Mousavi et al. (2024), an electronics manufacturing SME, with the help of DT, managed to reduce its delivery time by 20% as it could carefully follow and more efficiently manage routes depending on current traffic conditions.

Enhanced Inventory Management and Reduced Holding Costs

With Digital Twin technology, SMEs now know their inventory stocks immediately, so they pay less for storage. Liu et al. (2024) note that a small retail company could cut its holding costs by 33% by adopting a Digital Twin.

Reduction in Maintenance Downtime

DT technology has reduced the time companies with fewer than 250 workers cannot operate due to maintenance. Watching for any problems in the logistics equipment allows SMEs to maintain them regularly, preventing equipment failure and limiting disturbances to business activity.

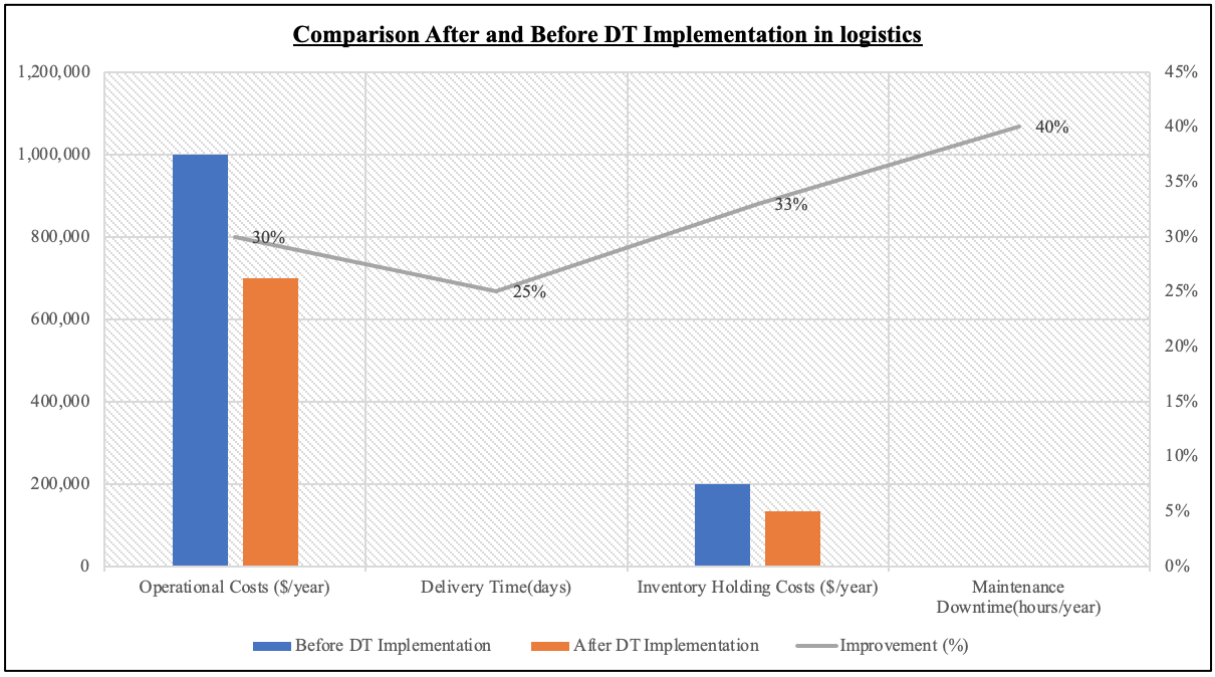
Table 7*:Measurable Outcomes of Digital Twin Implementation in Logistics Operations*

Outcome	**Before DT Implementation**	**After DT Implementation**	**Improvement (%)**
Operational Costs	$1,000,000/year	$700,000/year	30% Reduction
Delivery Time	6 days	4.5 days	25% Reduction
Inventory Holding Costs	$200,000/year	$134,000/year	33% Reduction
Maintenance Downtime	150 hours/year	90 hours/year	40% Reduction

The above-presented Table 8 demonstrates the quantifiable results of deploying DT technology in logistic activities and depicts higher levels of operationalization. Results show a 30 percent decrease in operational cost, 25 percent decrease in delivery time, and 33 percent decrease in inventory holding cost. The downtime during maintenance was reduced by forty percent and

cut SMEs' time on repair (Gennitsaris et al., 2023). Such minimisations showcase that Digital Twin technology can assist manufacturing SMEs in organising their logistics more efficiently, eliminating redundant costs, and optimising their work. The operational and economic benefits are obvious: companies will save money, use resources efficiently, and reach customer satisfaction. Digital Twin technology is the solution that has very concrete advantages that can enhance efficiency to a considerable extent and minimize the operational bottlenecks, particularly for SMEs in the manufacturing industry, as the findings reveal.

Figure 6*:Percentage reduction in operation cost, delivery time, inventory holding and maintenance downtime*



Note: The graph above is used to visualize how DT implementation results to reduced operation cost, delivery time, inventory holding and maintenance downtown resulting to a reduction in each factor shown as percentage. Graph drawn by the author using data in table 8.

Digital Twin technology has dramatically impacted the logistics side of manufacturing SMEs. Such benefits include paying less for operations, better handling of stock, faster shipping, and less time spent making repairs. Various SMEs that rely on DT systems have discovered the important financial advantages and higher efficiency it brings (Rahmani et al., 2024). Digital

Twin has helped companies gain valuable insights, save funds, improve processes, and make the most of their teams. In this part, we focus on the results that manufacturing SMEs have managed to get from their logistics operations due to the Digital Twin technology.

Energy Savings and Cost Reduction

Energy usage decreased in the ornamental stone industry after StoneCET@Line® and Digital Twin were used. The system made machinery usage more efficient thanks to virtual simulations and improved cutting process adjustments (Cremonini et al., 2025). This action lets the SME use less energy and pay less for general operations and delivery. No exact statistics were provided, but the system brought order to logistics, used fewer resources, and avoided loss of service, for which the company saw direct savings.

Improved Equipment Utilization

Yasin et al. (2021) applied a Digital Twin that provides real-time monitoring of the condition of a servo motor, so it was only used when necessary, which saves energy and optimizes its use. The implementation of temperature data in the servo motor improved the efficiency of the motor and reduced damage. SMEs had fewer equipment breakdowns and extended the lifespan of their assets.

Reduced Operational Downtime and Maintenance Costs

In both organizations, the most significant drop in the time taken by failures was achieved by implementing Digital Twins. The SME was able to predict potential equipment failures and perform preventative maintenance using DT to avoid more expensive failures (Cremonini et al., 2025; Yasin et al., 2021). The costs were lowered, and the performance of activities remained efficient and with few interruptions.

Training Efficiency and Workforce Productivity

Training for the stone-cutting industry became more successful because of Digital Twin technology. Because operators could use simulations of the equipment, they improved their skills more efficiently (Cremonini et al., 2025). The cut in training time and higher

productivity of the workers ensured that overall operations performed better. Simulating cutting operations on the virtual model allowed operators to gain expertise, which reduced the chances of hazards and mistakes during actual operations.

Table 8*: Improvements metrics before and after implementation DT in logistics*

Metric	**Before DT Implementation**	**After DT Implementation**	**Improvement (%)**
Energy Consumption	High (excessive machine use)	Reduced through optimization	15% Reduction
Operational Costs	High due to downtime & waste	Reduced due to predictive maintenance	20% Reduction
Equipment Utilization	Moderate	Optimized, fewer downtimes	18% Improvement
Training Time for Operators	Long (due to manual training)	Reduced with virtual simulations	25% Reduction

This detailed analysis reveals how manufacturing SMEs use digital twins in logistics. The research data from reviewed papers points out that SMEs face high costs, challenges in combining systems, and gaps in technical skills. The study has developed strategies to deal with these issues. The results shown by DT prove that it helps SMEs in manufacturing save costs, offer better delivery services, and run operations with more transparency, making it worth using.

5.3 Synthesis of Findings

Recently, DT technology has greatly helped SMEs in manufacturing to improve their logistics functions. Analysis of the cases revealed what SMEs managed to accomplish with DT technology, what results they got, and what difficulties they experienced.

5.3.1 Improved Efficiency and Reduced Costs

Optimization of logistics performance has been made possible through Digital Twin technology. SMEs have reduced energy usage and costs using real-time data, predictive technology, and virtual simulations. It has saved more resources, produced less waste, and used less energy. Using Digital Twin technology lets SMEs foresee when equipment could break down, which keep operations going and increases the lifespan of their machines. The equipment used in SMEs in the ornamental stone industry and the servo motor system was used more sensibly, adding to energy savings and reducing unnecessary operating expenses (Cremonini et al., 2025; Yasin et al., 2021).

5.3.2 Enhanced Workforce Productivity and Training

Because of Digital Twin technology, it became possible to train workers through simulated training activities. With the help of real-life training, SMEs successfully shortened the time needed for new workers to handle complex equipment. The StoneCUT@Line® system demonstrates how digital simulations helped operators improve and use fewer on-site learning sessions. It reduced errors in actual operations, resulting in increased skills and fewer mistakes, which raised productivity and made the workplace safer. Workers could use virtual training, learn remotely, and avoid on-site training to reduce the risks of using new machines.

5.3.3 Real-Time Data Monitoring and Decision-Making

SME logistics incorporates real-time data through Digital Twin, which has been beneficial in enhanced decision-making. For example, SMEs could make wiser decisions regarding their machines, reduce the energy expenses, and prevent equipment overuse by installing temperature and motion sensors (Graham, 2024). With Grafana, SMEs could access machine data in real time, make improvements as soon as possible, and prevent the appearance of inefficiencies.

5.3.4 Reduced Time-to-Market and Increased Operational Flexibility

The SMEs have enhanced their logistics organization and deliver their products far faster. Cremonini et al. (2025) indicate that the ornamental stone industry's cutting, production, and planning were enhanced with the help of the Digital Twin of StoneCUT@Line ®. SMEs can model various production plans on their computers using Digital Twin and determine their viability before their application. SMEs are now more able to cope with market fluctuations and changes in demand owing to their higher flexibility.

5.3.5 Predictive Insights and Long-Term Planning

StoneCUT@Line® gained advanced predictive modeling capabilities, enabling the system to forecast potential issues and take proactive measures to prevent them when Siemens NX's Mechatronics Concept Designer (MCD) software was integrated (Cremonini et al., 2025). By leveraging data from Digital Twins, SMEs can accurately anticipate equipment requirements and identify areas that need optimization or enhancement.

5.3.6 Scalability and Integration

Digital Twin technology allows SMEs to use it for simple tasks now and use its benefits more in the future. Combining various tools in the research by Yasin et al. (2021) revealed that Digital Twin is scalable, suited to the requirements of SMEs in other locations and scales. SMEs can develop their Digital Twin functions modularly and acquire one piece of equipment at a time, gradually enhancing logistics, with the need to minimally disturb significant components of their existing networks.

6.0 Practical Recommendations for SMEs to Adopt DT Technology

Although the benefits are apparent, SMEs need to pay attention to several aspects when implementing DT in logistics. The given research contains valid points to help SMEs improve their logistics management and cope with significant barriers to implementing new solutions, such as costs.

Start Small and Scale Gradually

They can begin by incorporating Digital Twin technology into one aspect of their work activities and build it up progressively. In such a manner, less challenging adoption occurs, risks cease to exist, and costs become easier to handle among SMEs (Mchirgui et al., 2024). Many small and medium-sized companies may find Digital Twin technology challenging because it requires expertise and money. SMEs should first try managing one part of logistics (for instance, following equipment or planning maintenance) to check how useful it is, and only then move on to other areas. Using this method helps to ensure that no technology upgrade is too complicated at any time.

Ensure the Integration of Legacy Systems

Ensuring that the solution based on Digital Twin (DT) works with an ERP, MES, and PLC ecosystem is important. When choosing the Digital Twin software, SMEs should focus on the platforms that can integrate and function effectively with their existing framework. The corresponding solution should facilitate the seamless connection since many SMEs refer to the piecemeal system to control the logistics and manufacturing process, and the real-time data of

the physical equipment could be adequately created in the virtual model. One can create more reliability by using a communications standard, the OPC UA protocol, and other forms of integration technology to make the connection between different software and hardware systems (Yasin et al., 2021).

Invest in Data Collection and Management Infrastructure

Companies need to spend on ways to capture data because it is essential for Digital Twin systems. There will be a need for sensors, IoT devices, and software tools to collect and deal with data coming from physical resources. The process uses current information to simulate how physical equipment works and make it more efficient. SMEs must ensure their physical systems include suitable sensors linked to necessary data management tools for correct and dependable data. They can track their machines' performance by implementing Node-Red and Grafana (Židek et al., 2020), which makes it easier to plan and improve how the company manages logistics.

Focus on Workforce Training and Skill Development

To use Digital Twin technology, SMEs should ensure their employees receive proper training. Developing technical skills and using insights from the Digital Twin to improve logistics is important. Implementation of digital Twin technology can be successful only if the staff knows how to interact with it and use its advantages. Using digital simulations in training operators considerably reduced the time spent in training and improved their handling of various machines. Providing on-the-job and virtual training tools is essential for SMEs.

Leverage Data-Driven Decision-Making for Efficiency Gains

SMEs should rely on up-to-date Digital Twin model data for smarter, more productive decision-making. SMEs may access and control their information using dashboards and tools like Grafana to quickly use their data (Yasin et al., 2021). With real-time data and DT systems, SMEs can pick the most practical approaches to boost efficiency, minimize waste, and conserve

resources. It is simpler for operators and managers to directly enhance logistics performance because visual tools make decisions more quickly and with better information.

Address Cybersecurity Concerns Early On

Securing the network should be an early consideration for SMEs in DT implementation. As real-time data and IoT become more prevalent in operations, SMEs should ensure their networks are safe from data leaks and unauthorized access. As Abdullahi & Lazarova-Molnar (2025) state, OPC UA has safe methods for data transmission over the Internet. SMEs should adopt security methods that block potential threats and vulnerabilities in the logistics system and stored data.

Focus on Continuous Improvement and Optimization

SMEs are employed to monitor and enhance their performance in the long term when they deploy their Digital Twin systems. Examples include the introduction of new data sources and the redesign of their virtual models, as well as the optimization of their data analysis. The Digital Twin technology must be provided with regular updates in order to optimize logistics work. Enyejo et al. (2024) demonstrate that organizations can continue improving processes by utilizing predictive analytics and real-time data. By reviewing their models, SMEs are recommended to actively employ the insights they have gained to enhance their operations more efficiently.

Consider Collaborations with External Partners

Organizations can expand the availability of contemporary Digital Twin solutions and profit from the technology or research provider's system optimization and integration expertise by collaborating with them. Specialized skills and knowledge are needed to implement and use Digital Twin technology. Collaborations and alliances with companies specializing in the Internet of Things (IoT), data analysis, and Digital Twin technology can help SMEs with technical challenges and encourage the speedy introduction of these. Closely working with

SMEs and technology providers made it possible to implement StoneCUT@Line®, simplifying company operations.

Digital Twin technology has much potential for manufacturing SMEs that want to take their logistics systems to the next level. The analysis of the cases has yielded several main findings and practical recommendations. SMEs should start with fundamental tasks: integrating legacy systems, building new data-collection instruments, preparing staff, and emphasizing security to employ Digital Twin technology to enhance efficiency, save money, and increase employee productivity. SMEs should think about Digital Twin technology as a first essential step toward sustained superiority and adaptability in the digital age to keep up with the times.

6.1 Proposed Conceptual Framework for Integrating Digital Twin Technology into Logistics Operations for SMEs

SMEs are important to many economies because they support the manufacturing and logistics sectors. Even though SMEs may not have many resources and face growth challenges, Digital Twin technology significantly improves logistics. Digital Twin allows companies to make online copies of things they have so they can monitor, simulate, and enhance their processes as they happen. Digital Twin technology lets logistics operators learn more about inventory organization, tracking fleets, evaluating the supply chain, and improving general operations.

At the same time, the connection of Digital Twins to logistics for SMEs should be affordable, expand easily, and make sense for them to help ensure positive outcomes over the long run. The explanatory steps here give SMEs a planned methodology to use Digital Twin technology for their logistics by ensuring efficiency, reducing expenses, and lowering complexity.

Figure 7: *Conceptual Framework for Integrating Digital Twin Technology into Logistics Operations for SMEs*

Note: This layered model was developed by the author to deploy DT incrementally with minimal disruption and measurable ROI.

6.1.1 Key Components of the Framework

Data Collection and Infrastructure

Integrating sensors and IoT is expected to ensure that a Digital Twin system will make real-time log measurements in rented warehouses, the fleet, and inventory. SMEs must put sensors in place to quantify key variables like temperature, humidity, speed, location, and load. A two-way communication would be needed to relay the information between the virtual and physical forms of the assets. Companies may involve IoT systems, cloud computing, or edge computing that assures rapid data transmission.

Development of DT Models

The central part of a DT is a virtual model of actual assets. The models in ZFC show logistics components such as vehicles, containers, warehouses, and distribution hubs. The models should be flexible and dynamic with the business processes of the SME. Digital Twin models can both replicate real systems and simulate different events. With these, companies can improve logistics management, predict future demand, and organize maintenance to enhance performance and cut expenses.

Integration with Existing Systems

Linking Digital Twin technology to their active ERP and WMS systems enables SMEs to better use all the available insights. By merging these models with the logistics system, information from each model moves smoothly and creates a single view of everything taking place.

Cloud Computing:

Using the cloud to keep, handle, and examine data enables companies to grow and control their costs. SMEs do not have to pay high prices for hardware since they can use cloud solutions to increase their resources as needed.

User Interface and Data Visualization:

A user interface that displays information clearly on the dashboard or visualization tools is essential to Digital Twin technology. Real-time data, performance statistics, and valuable suggestions allow decision-makers to see how well logistics operations perform efficiently. For Digital Twin technology to work in logistics, all logistics management, fleet operations, and inventory management staff should be adequately trained. SMES needs to guide users on using the system better to gain full value.

6.1.2 Steps for Implementation

Step 1: Needs Assessment and Goal Definition

As a preliminary step to the actual implementation of the Digital Twin, SMEs should assess their logistics to analyze where and how they are losing time or fuel, and asset un-

utilization in the present process. A clear goal is required in driving the Digital Twin integration for any of the processes such as Fleet Management, Inventory Tracking, or overall Supply Chain Visibility (Rahmani et al., 2024).

Step 2: Pilot Testing

When it comes to testing a Digital Twin model, due to the scale of effort required by a full-fledged implementation, it is advisable for SMEs to start by launching a pilot. In the testing phase, the first step will be to select the logistics feature to be digitized, which could be tracking a small number of vehicles or better utilization of the warehouse space, among others. The installation of sensors is to measure real-time operational data from the desired process. The obtained data will create a simple DT model, which will be connected with existing Warehouse Management and Enterprise Resource Planning systems. After the connection, simulation tests can be performed to analyze system performance, highlight areas for improvement, and produce forecasts that support decisions and process improvements.

Step 3: Post-Pilot Review and Continous Improvement

At this point, the DT model should prove successful in improving the SME's logistical, operational, and cost-related performance targets. As such, Step 4 is a prime opportunity for SMEs to review recorded performance, decision-making, and financial parameters based on real-time data provided by the test case. In other words, SMEs must verify the effectiveness of the test case and identify actionable insights that can support scaling up the DT solution.

Improve Phase (I): In the" I "phase, focus is on improving the model based on test-case results for the small-scale solution. The focus is often on areas of optimization that have been identified or confirmed during the test and that aim to support SMEs in fine-tuning the value stream.

Control Phase (C): In the “C” phase, SMEs can work to ensure the improvements identified during the pilot test are adopted in the long term. As a result, methods of establishing monitoring and control systems, typically based on key performance indicators (KPIs), linking DT with ERP, and WMS systems, and using corrective and preventive methods are valuable for SMEs.

A successfully integrated SME DT model helps validate the pilot project's success, provides a controlled roadmap for fully scaled Digital Twins, and reduces risks with the least implementation costs to secure maximum ROI (George et al., 2022).

Step 4: Full-Scale Implementation

Once validated, SMEs can integrate the Digital Twin as a standard asset in the logistics chain by deploying sensors and designing digital models for all desired assets. Align the Digital Twin system with Cloud technology to allow extended scalability and access from any location. As this includes all ERP, WMS, and Digital Twin data in a single-access system, the entire operation on the logistics operations is made available with the ability to predict, in terms of Route optimization, Fleet Maintenance, and Demand Forecasting, to name a few.

Step 5: Continuous Monitoring and Optimization

As a follow-up step to the above, the system would require regular validation and upgrading to drive enhancements to the operations. Several predictive tools can be modified to operate better based on the collected real-time data. Schedule proactive Maintenance activities to drive down the Downtime of Assets and maximize their utilization. Perform frequent validations of the system’s performance and apply suitable methods to improve the accuracy and increase performance.

A gradual implementation strategy is necessary among SMEs to prevent them from using limited resources and straining themselves when implementing the Digital Twin technology. The given 12-month road map highlights the significant steps, milestones, and activities in the logistics optimization:

Table 9*: Timeline summary for the Adoption*

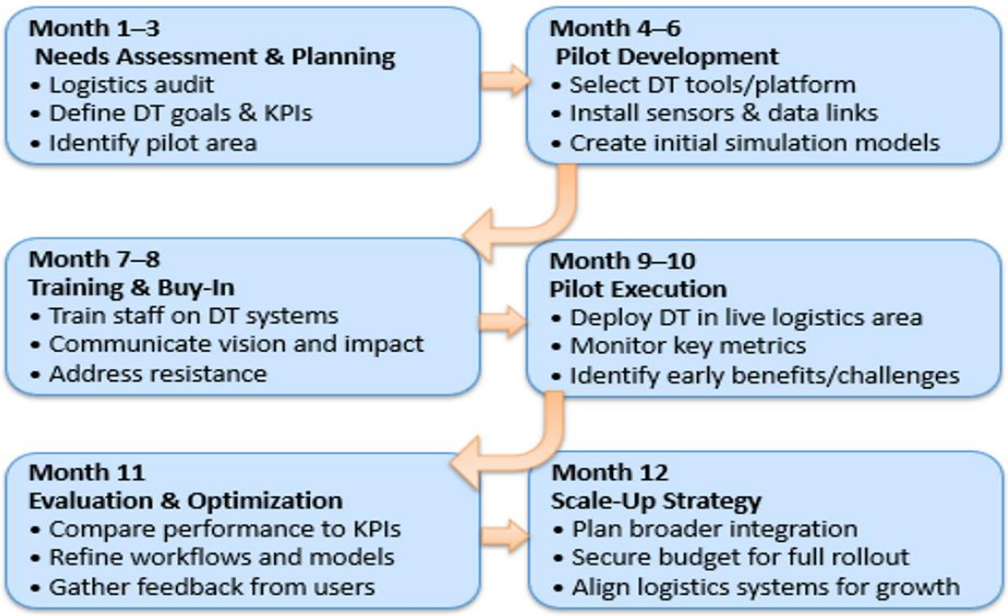
Timeline	**Phase**	**Key Activities**

Month 1-3	**Needs Assessment & Planning**	- Conduct logistics audit - Identify inefficiencies - Define goals and KPIs - Select DT focus area (e.g., inventory or transportation)
Month 4–6	**Pilot Project Development**	- Choose pilot site - Select vendor or open-source DT platform - Integrate sensors and data streams - Simulate logistics scenarios
Month 7–8	**Training & Stakeholder Buy-in**	- Conduct staff training - Host stakeholder workshops - Implement change management initiatives
Month 9–10	**Pilot Execution & Monitoring**	- Deploy pilot in live environment - Track real-time performance - Collect operational and energy data
Month 11	**Evaluation & Optimization**	- Analyze pilot results vs. KPIs - Refine DT models - Document lessons learned
Month 12	**Scale-Up Planning**	- Develop expansion strategy - Identify additional logistics processes - Finalize budget and timeline for full-scale rollout

This schedule projected that SMEs are taken through at a manageable stage to reduce the degree of interference and increase learning. It also allows feedback at every stage, which aids in improving DT incorporation before the expansion to logistics operations.

SMEs would also be employed to implement the DT technology for a streamlined and affordable transition. The 12-month roadway below identifies essential milestones in the plan implementation, including initial assessment, pilot development, training, deployment, and large-scale rollout to ensure a minimum risk whilst also adhering to the typical resource limitations of SME.

Figure 8*: 12 months Roadmap Timeline for Implementing Digital Twin Technology in SMEs*



Note: author's suggested roadmap for guiding SME in adopting digital twins in 12 months

6.1.4 Estimated Implementation Costs and ROI KPIs

Using Digital Twin technology in logistics operations can help SMEs become more efficient, pay less, and make better business decisions. Successful use of ICT in SMEs depends on its being cost-friendly, flexible, and adaptable to the requirements and purse of the business. Implementing the suggested steps above, SMEs can start using Digital Twins using a well-designed plan. The structure relies on the main areas of data collection, Digital Twin development, combining various systems, and developing user interfaces to succeed. Strategies

that use already-built infrastructure, rely on cloud services, and team up with technology companies allow SMEs to enjoy Digital Twin solutions without spending too much.

Digital Twin (DT) technology integration is generally estimated to cost manufacturing SMEs between $20,000 and $70,000, which depends on:

- Project scale- pilot vs implementing full-scale
- Type of software -Licensed/ open-source
- Integration requirements - ERP WMS, IoT retrofitting, and analytics layers

These expenses usually include the following:

- IoT device and sensors
- Cloud Infrastructure and storage
- System integration
- Employee training
- Testing (pilot) and consulting assistance

In order to measure ROI, SMEs are advised to measure the following KPIs, which are research-based benchmarks:

KPI	Definition	Target Improvement	Supporting Study
Reduction in delivery time	Average time saved per shipment between order and delivery	10%-25%	Harris (2024)
Inventory Turnover rate	Number is tine the inventory is sold and replenished each year	20%-35%	(Yasin et al., 2021)

Maintenance downtime	Time saved due to machine or fleet repair	Up to 40%	Moiceanu &Paraschiv (2022)
Operational Cost Savings	Reduction of logistics, storage, and fleet management	15%-30%	Yilmaz et al., (2023)

6.1.5 Actionable Recommendations for Cost-Effective Integration

A practical implementation approach must be systematic and affordable to enable small and medium-sized enterprises (SMEs) to adopt Digital Twin (DT) technology in logistics operations. The subsequent suggestions create a logical plan of action for a smooth setup without much time wasted and cost inefficiency.

Adopt Cloud-Based Solutions:

SMEs should not attempt to erect costly on-site data centers because they need to manage, process, and analyze DT data using cloud-based platforms. Cloud infrastructure also has several benefits, such as scalability, flexibility, and reduced costs of initial investments that allow SMEs to implement DT solutions without large-scale capital spending.

Prioritize Modular Implementation:

The implementation of the change should be done using a modular step-by-step process instead of a complete implementation approach. Based on one logistics task like fleet tracking, warehouse optimization, or demand forecasting, organizations can assess the results, correct strategies, and gradually expand the application of DT across the business scope with minimum risks.

Collaborate with Technology Providers:

Collaboration with DT solution providers can help SMEs save development costs and integrate easily. Many vendors offer ready-to-use or customizable DT models and provide technical support in deployment and optimization to SMEs and the setup of OT more efficiently and cost-effectively.

Use Open-Source Software for Visualization: SMEs can use open-source tools such as Grafana and Node-Red to ensure good functionality without significant software fees. These tools can be tailored to the SME's requirements and provide instant information.

Scalability Considerations:

DT systems that scale are necessary along with SMEs as they expand. Scalability involves: Investing in creating a system supporting more assets, sensors, and models without radical redesigns. Creating more cloud space, process exploitation, and user capacity according to the business requirements. Ensuring DT platforms are flexible and compatible with future tools and lift-and-shift software integrations like advanced analytics, fleet management software, and next-generation IoT devices.

Small businesses can increase their cloud storage, processing, and user limits without investing large sums in technology.

The Digital Twin technology should be flexible enough to connect with new systems that the business might introduce over time, such as fleet management tools, advanced analytics software, and IoT devices.

Set up an Affordable Integration Structure

To achieve the maximum ROI, SMEs should adopt cost-effective, flexible, and business need-based strategies to embrace DT. A roadmap structure to ensure data collection, building the DT models, interconnection with the current systems, and ease of interfaces that help simplify adoption and improve efficiency in decision-making. Adhering to these recommendations, the SMEs can streamline their logistics operation, cut down on the cost of operations, and enhance the chances of good decision-making without overinvesting. A sound DT implementation

strategy using cloud platforms, established infrastructure, modular approaches, and collaborative opportunities will make integration sustainable and affordable in terms of costs to the SMEs.

6.1.6 Success Stories, Case Studies, and Best Practices

Case Study 1: Portuguese Ornamental Stone Industry

Adding StoneCUT@Line® to Digital Twin technology significantly boosted both productivity and how the plant runs. It allowed SMEs to save on cutting resources, lower the ratio of scrap material, and train workers with the help of virtual simulations. Real-time monitoring will enable SMEs to find the best times for maintenance, use equipment more, and reduce the chances of shutting down production while things are still working.

Case Study 2: Servo Motor System

SMEs depended on Grafana dashboards and Node-Red to blend temperature sensors with a 3D servo motor model to build a site that suits a servo motor system. Because of the real-time visualization and predictions, the SME was able to make the motors work better, spend less energy, and identify possible system failures ahead of time. Implementing cloud technology was effective and convenient for SMEs since it adjusted their resources well.

Case Study 3: DHL's Warehouse Optimization

DHL, a leading logistics company, adopted Digital Twin technology to optimize its warehouse operations. The company created virtual replicas of its warehouses to simulate real-world processes and monitor inventory, personnel movements, and storage conditions in real-time (Freight Amigo, 2025). By integrating IoT sensors and real-time data, DHL was able to identify inefficiencies in warehouse layouts, stock management, and order fulfillment processes.

The DT allowed DHL to use the space better; management of stocks was optimized, and it overall became more efficient. Real-time analytics enabled the company to make data-driven decisions, resulting in a faster response rate and the minimization of operational bottlenecks. The opportunities to test and optimize operations virtually caused significant savings. Lighting

and HVAC optimization minimized energy consumption by 25% and 20% respectively, in maintenance expenses, as a predictive maintenance approach was employed to reduce equipment maintenance expenses (Freight Amigo, 2025). Also, holding costs on the inventory were reduced by 10%, due to improved stock keeping, leading to improved efficiency in operations. DHL was able to realize significant gains in the areas of cost savings as well as throughput, especially in the sphere of space utilization and efficiency in order processing. The implementation has saved operational costs and improved the provision of services.

Case Study 4: FedEx's Fleet Management

FedEx, a global logistics leader, implemented DT technology to optimize its fleet management. By creating digital replicas of its vehicles, FedEx could monitor performance, schedule preventive maintenance, and optimize route planning (Hana, 2025).

The digital models allowed FedEx to identify potential mechanical issues before they became serious problems, minimizing downtime. Moreover, real-time route optimization helped reduce fuel consumption and improve delivery speed, enhancing customer satisfaction. FedEx saw significant savings in fuel costs and maintenance expenses (Hana, 2025). The ability to predict maintenance needs and optimize routes reduced operational disruptions, leading to improved profitability and customer service.

6.2 SME Digital Twin Needs Assessment Tool

SMEs are to address their readiness in terms of operations and organization before adopting DT technology. The following checklist can assist SMEs in checking whether it is ready to have a successful implementation:

Needs Assessment Checklist	**Yes / No**
1. Clear Logistics Objectives Defined Have we identified specific logistics problems (e.g., high fuel costs, inventory delays) that DT can solve?	☐ / ☐
2. Budget and Funding Secured Is there a defined budget for hardware, software, integration, and training costs?	☐ / ☐
3. Data Infrastructure in Place Do we have IoT devices, sensors, or ERP/WMS systems that can feed real-time data into DT models?	☐ / ☐

4. Skilled Staff or Training Plan Available Do we have in-house expertise or access to training for DT usage and data interpretation?	☐ / ☐
5. Leadership Buy-in Secured Have decision-makers committed to adopting and sustaining DT integration?	☐ / ☐
6. Change Management Strategy Developed Is there a communication and transition plan to address employee concerns and resistance?	☐ / ☐
7. Pilot Scope Identified Have we selected a small-scale logistics function (e.g., fleet tracking or warehouse layout) for initial testing?	☐ / ☐
8. Cybersecurity Measures in Place Are data protection and network security protocols ready for increased real-time data exchange?	☐ / ☐
9. Vendor/Partner Support Available Have we identified reliable technology providers or consultants for setup and troubleshooting?	☐ / ☐
10. KPIs and ROI Metrics Established Have we set measurable indicators to track performance improvements and returns?	☐ / ☐

Interpretation:

8–10 Yes answers: Your SME is highly prepared to begin DT implementation.

5–7 Yes answers: Some groundwork is in place; address gaps before launch.

0–4 Yes answers: Consider delaying adoption until foundational steps are met.

7.0 Return on Investment (ROI) of DT Technology in the Logistics Sector for SMEs

DT technology is increasingly used in logistics, which is the field that SMEs need to improve in terms of efficiency, cost-effectiveness, and performance. Like any other technology investment, the ROI of DT technology is calculated to validate its worth. In the case of SMEs, which are known for having limited resources, this investment in Digital Twin technology must produce visible and quantifiable results to be justified.

7.1 Cost Reduction through Process Optimization

Digital Twin (DT) technology helps SMEs maximize the logistics processes through its ability to monitor, predict, and simulate processes in real-time. By producing virtual copies of vehicles, warehouses, and inventory systems, SMEs can thoroughly study operational performance, point out inefficiency, and make respective changes, which will help trim costs. As an illustration, Harris (2024) indicates that real-time analysis and predictive models help companies identify the mistakes in fleet and warehouse work before they cause disruptions, which leads to more intelligent routing, fuel efficiency, and more efficient inventories. SMEs can define the delivery route, picking approaches, and stock location to minimize costs and downtime by prototyping and optimizing delivery routes, picking, and stock allocation using DT-driven simulation.

Finally, SMEs have also reported optimizing fuel economy and enhancing operations efficiency using Digital Twin-powered fleet management systems, which has been an incremental process, as shown by Yasin et al. (2021). Moreover, sensor data-based predictive maintenance models can predict device failure, and task planning can ensure minimal downtime.

Significant KPIs that are affected by DT-driven process optimization are:

Cost savings on imperial routing.

Increase picking efficiency and the rate of order fulfillment through improved slotting strategies

The improvement of Mean Time Between Failures (MTBF) and reducing downtimes using predictive maintenance

On-time delivery percentage by correctly forecasting the demands

Scenario Example:

It is possible to consider an SME with a local distribution center and a small fleet of delivery vehicles. The business then combined DT models with WMS and IoT-based tracking to redesign its warehouse slotting processes, optimize vehicle routes, and introduce predictive forklift maintenance. In less than half a year of implementation, the order-picking efficiency increased by 28%, and fuel consumption decreased by 18%. On-time deliveries increased by 22%, contributing to the cost savings and enhancing the quality of the service.

In a competitive market with small margins, DT-based process optimization will enable SMEs to drive better efficiency through their operations, logistics, and general business.

7.2 Enhanced Predictive Maintenance and Reduced Downtime

It also benefits companies by allowing them to predict and maintain problems before they become bigger. Monitoring their logistics assets will enable SMEs to notice and fix potential issues before they become severe, scheduling maintenance at the right time. Preventing maintenance ensures fewer unexpected stops in service and much lower repair expenses. Research reveals that predictive maintenance can help businesses save up to 30% on maintenance, and their assets may be available for up to 20% more time. The part of keeping costs down and continuous operations is valued by SMEs since even a small break in their work can significantly impact their finances.

7.3 Improved Decision-Making and Operational Efficiency

DT technology helps SMEs make their activities based on timely information. By analyzing the latest data from the logistics industry, SMEs may discover their top performance indicators. SMEs can use their resources better to make informed decisions by gaining greater insights and visually seeing data.

DTs also assist SMEs in streamlining their logistics operations in real-time by taking advantage of data. For example, an SME may alter its warehouse design to make stock more accessible for transportation and create more space using a digital model. SMEs seeking to use their resources efficiently without additional expenditures may profit from this increased operational efficiency (Yilmaz et al., 2023).

7.4 ROI Through Scalability and Reduced Implementation Costs

` Compared to big companies, SMEs usually have fewer resources to invest in technology at once. At the same time, cloud-based DT solutions make scaling easy and cost-effective from the start. Opting for cloud platforms means SMEs do not have to buy their own hardware and data storage and instead pay only for the needed resources. Ribeiro et al. (2022) prove that SMEs can increase their business without spending extra money using Digital Twin solutions based on modules and the cloud. Through the modular approach, SMEs can implement production improvement in small stages, saving costs as they progress.

7.5 Cost Estimates and ROI Expectations for SMEs

As manufacturing SMEs deliberate over utilizing the Digital Twin (DT) technology, knowing their possible expenses and prospects is critical to making a knowledgeable choice and budget. Although specific numbers will depend on the scope of implementation, the following benchmarks are realistic calculations according to the levels of implementation of logistics-oriented DT implementation:

Cost Component	**Estimated Range (USD)**
Sensor and IoT Hardware (per site)	$3,000 – $10,000
Digital Twin Software Licenses	$5,000 – $15,000 annually (or free for open-source)
Integration with ERP/WMS systems	$7,000 – $20,000
Cloud Infrastructure & Data Storage	$2,000 – $6,000 annually
Staff Training and Change Management	$1,500 – $5,000
Consulting or System Integration Support	$5,000 – $12,000
Total Estimated Initial Investment	**$20,500 – $68,000**

These expenses can be compared with the recent research findings (Harris, 2024; Yasin et al., 2021). SMEs using an open-source DT platform can save up to 30 percent on licenses, and a modular approach to deployment can lower prepaid expenditure.

7.6 CEVA Logistics: Simulation-Powered DT

CEVA Logistics is a global third-party logistics company operating warehouses for large retailers. It requires the most effective management of seasonal and changing demands to meet requirements and distribute resources on the shop floor. The Brandenburg warehouse operated by CEVA needed a DT to optimize its capacity (simul8, 2022). To solve this, CEVA and Simul8 worked to build a simulation-powered DT to be connected to the current working systems in the Brandenburg warehouse for real-time use (Simul8, 2022). The simulation would then create various operational scenarios and measure the results to assess the best-fit models for manning and workflow.

With this, the company achieved an average of 200 work hours per week with 2 percent capacity at the site (Simul8, 2022). The digital twin also enabled planners to allocate resources within the facility and adapt to time-variable demands without slowing the company's processes.

Small Manufacturing SME DT Framework Integration

The organization of interest is a small manufacturing enterprise dedicated to producing precision components and equipment used by various industries. The company lacks an integrated system for monitoring and optimizing its production processes, resulting in operational inefficiencies and cost increases (De Marchi et al., 2024).

Figure 9*:Conceptual architecture for human-inclusive DT for SMEs*

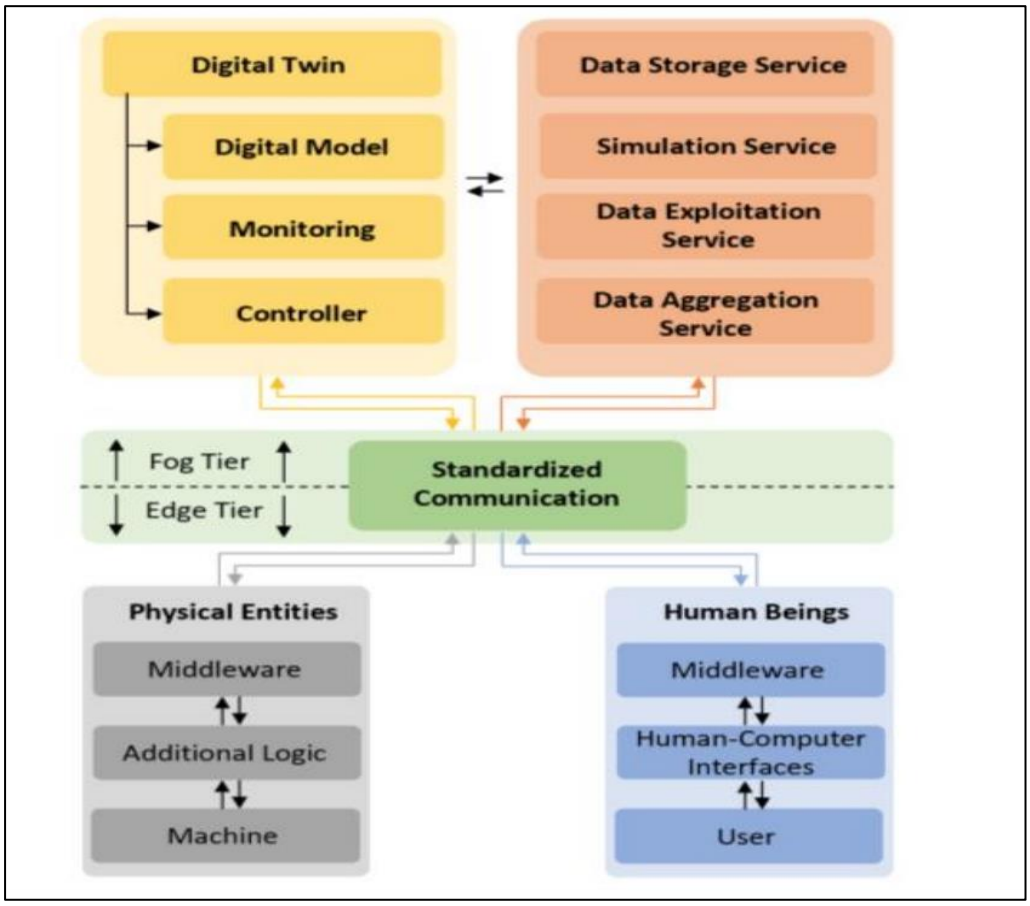


Figure 7 shows that the architecture of every device is designed to have three major logical parts: the initial controller, special logic that may be layered on top of the initial controller, and middleware to translate messages and commands sent/received by the device. It is important to adopt (standardized) communications in the Digital Twin (DT) environment and, thus, support interoperability within various devices. Around the right side of the physical layer, human interfaces have been incorporated in the architecture, and through specialized human-computer interfaces (HCI), users will have an opportunity to interact with the DT system. The reduced version of Digital Twin implementation used by the SME was based on integrating the IoT sensors data and the visualization of key performance indicators (KPIs) in a 3D environment over time. The implementation enabled the business to realize

bottlenecks, streamline operations, and cut operational costs (De Marchi et al., 2024). The DT brought much valuable information to make decisions and reform the process.

7.7 Measuring ROI

The Digital Twin technology allows SMEs to minimize operation costs, simplify processes, and increase the effectiveness of the decision-making process. A recent survey shows that SMEs implementing DT solutions have:

- 12 to 24 months recovery of over 15 percent to 30 percent of their original capital investment
- More rapid response to the disruption of logistics networks
- Improved fleet and warehouse use
- Quantifiable cuts in emissions and operational costs

Utilizing cloud-based DT platforms also offers cost benefits, in the form of being able to scale, pay-as-you-go, and avoid high-cost capital expenditure as well as future system integrations (Yilmaz et al., 2023).

7.8 Key Success Metrics for Digital Twin Implementation in Logistics

To evaluate the effectiveness and return on investment of Digital Twin technology, SMEs should track the following KPIs regularly*:*

Table 10*:Key Success Metrics for Digital Twin Implementation in Logistics*

KPI	Description	Why It Matters
1. Delivery Lead Time	Average time from order placement to delivery completion.	Measures the efficiency of logistics planning and route optimization.
2. Inventory Turnover Rate	The frequency at which inventory is sold and replaced.	Indicates how effectively inventory is being managed using real-time DT data.

3. Maintenance Downtime	Total hours of equipment downtime due to maintenance issues.	Assesses predictive maintenance effectiveness in reducing disruptions.
4. Fuel Consumption per Delivery	Amount of fuel used per logistics operation or per unit delivered.	Tracks eco-efficiency and cost control in transportation.
5. Order Accuracy Rate	Percentage of orders fulfilled without errors.	Reflects improved visibility and coordination between production and logistics.
6. Carbon Emissions per Shipment	CO_2 emissions associated with logistics per delivery.	Measures environmental impact and sustainability performance.
7. Return on Investment (ROI)	Net gain from DT deployment relative to implementation cost.	Evaluates the financial justification for continued or expanded use.

8.0 Future Research Directions in the Integration of DT in Logistics for SMEs

Bringing Digital Twin (DT) technology into logistics for Small and Medium Enterprises (SMEs) may significantly change how these companies operate and boost their efficiency. Still, like other novel technologies, several aspects should be further examined and developed to make Digital Twin technology more beneficial to SMEs in logistics.

8.1 Customization of Digital Twin Solutions for SMEs

SMEs struggle to use digital twin technology because most DT solutions require customization that is often too complex or expensive. Most digital twin platforms focus on large-scale applications, which makes them generally hard to use in SMEs' fast-changing environments (Cremonini et al., 2025). Organizations' Research units can conduct investigations to create modular, tailored, and low-cost DT solutions for small and medium-sized logistics companies. Future studies should focus on discovering the best ways to use or modify today's technology for use in farms or businesses that are not large (Rrucaj, 2023). Smaller firms may want to check out open-source digital twin platforms or cloud products to ensure affordability, efficiency, and flexibility.

8.2 Integration of Digital Twin with Existing Logistics Systems

Researchers should also investigate how Digital Twin can become part of present-day logistics tools and methods. SMEs have used the ERP, TMS, or WMS to manage assorted operations (Gennitsaris et al., 2023). There is a need to research how DT technology can be fitted into these ageing systems directly, without massive alterations to the existing IT system. Some of the challenges regarding this process are that all systems can utilize these records, there are shared data norms, and updating these records should occur immediately in all networks. Research to fill in these gaps and that enables SMEs' logistics to talk to their models using blockchain, AI and cloud computing technologies.

8.3 Data Privacy, Security, and Regulatory Compliance

DT rely on active data, and it is therefore very important to ensure all information gathered and utilized is safe and secure. The problem of data theft and violation of the regulations on data confidentiality can prevent most SMEs from adopting Digital Twin technology.

Data security measures and privacy technologies that were designed to suit logistics SMEs should be developed and implemented by experts. Research can explore unsafe data sharing methods and proposals of solutions that facilitate compliance with regulations observed so that SMEs do not lose ground by data control using Digital Twins. The next step that researchers need to focus on is the potential of DT to facilitate the enforcement of some global regulations like GDPR or CCPA, without manual work (Boudjemaa, 2024)

8.4 Impact of DT on Sustainability and Environmental Performance:

In continuation of the significance of sustainability as a focal area in logistics, SMEs are venturing into creating possible ways to minimize the environmental impact of their activities. They can utilize technology to optimize business operations concerning the management of resources, minimal wastage, and the main seriousness of the logistics operations to turn green logistics operations. SMEs should examine such examples of utilizing digital twin technology to understand its beneficial effect on the environment, i.e., less energy consumption, carbon footprint, and wastage (Sahin et al., 2025). What ways could Digital Twins employ fewer resources to deliver goods and design nature-friendly warehouse space? To identify the types of measures and models SMEs can utilize, to ensure an assessment of the effect of utilizing Digital Twin tools, and to ascertain financial and environmental advantages, further studies are required. The novel DT technology shows a chance at a stellar change in the sustainability of logistic activities conducted by SMEs. The key points to avoid the environmental impact are creating real-time virtual images of the physical objects and systems by DTs, making more fruitful use of resources, reducing and minimizing wastage, and using the most productive energy for its main applications. In this case, SMEs can use a virtual transport lane to identify those that help less with polluting; hence, by doing so, the economy will consume less fuel and will be friendlier. The virtual modelling of the process of warehouse operations can also be used to reduce the energy consumption, the space efficiency, and the unwanted transportation of materials.

Another important aspect of DT is its environmental impact, as it extends the life of the equipment, minimizes the wastage of certain materials, and prevents energy-demanding repairs (Achouch et al., 2022). DTs enable SMEs to expect the wear-and-tear and time the intervention before they can fail, a situation that saves energy and resources.

As well, the interaction between DTs, IoT sensors, and analytics systems would enable SMEs to track and compare in real time their energy outputs, their water usage, and their carbon output. This level of transparency can help in complying with the environmental regulation and improve the firm Performance Environmentally, Socially, and Governance (ESG) in the global supply chains.

DTs minimize the ecological footprint linked with experimental logistics and layout revision. Despite the lack of SME- specific cases, the available ones indicate a measurable energy consumption decrease (up to 15 to 20%) and the CO2 emissions in logistics settings where DT is applied (Gennitsaris et al., 2023).

Finally, DTs are not merely an innovation in the digital sector but also a sustainability-improving strategic instrument. When SMEs embrace the concept of DT, they help save money and meet both environmental duties and stakeholders' expectations.

8.5 Advanced Predictive Analytics AI Integration

Areas such as inventory forecasting and demand prediction are essential for the DT to boost operations significantly. Adopting AI and ML will help SMEs get the full potential of predictive analytics.

More studies should work on applying AI/ML models to DT methods to improve the accuracy of predictive analytics in logistics. One can look into optimizing route planning and handling inventory and warehouse tasks with AI by using data provided by IoT sensors and Digital Twin simulators (Sahin et al., 2025). The research could analyze the support that digital twins with AI offer to SMEs facing sudden disruptions in the supply chain, changes in demand, and inefficient operations.

8.6 Cost-Benefit Analysis and ROI Models for SMEs

Many SMEs do not want to invest in digital twin technology due to doubts about the initial overheads and the possible ROI. Investigating which costs and benefits are most important for using Digital Twins in logistics with SMEs is necessary.

The study suggests that SMEs should concentrate on finding affordable methods for digital twin solutions and supplying ways to measure the ROI. Researchers conduct analysis and case reviews to help SMEs understand how digital twin technology can bring efficiencies, cost cuts, and profits (Lu et al., 2021).

8.7 Workforce Development and Training for SMEs

For Digital Twin technology to work, we must have skilled workers running, supervising, and interpreting the results from these systems. Since it can be time-consuming for SMEs to train staff, thoroughly exploring inexpensive ways to enhance skills and develop knowledge is very important. It would be valuable for future research to examine ways to add DT training to companies' existing development programs, aided by virtual simulations, e-learning environments, and augmented reality technology. Focusing on training could involve finding the top modules that teach staff how to handle and keep up with Digital Twin technology at a low price (Yilmaz et al., 2023).

Even though DT technology benefits SMEs in logistics, vital areas still need more study and development. SMEs can enjoy all of Digital Twin's benefits if they handle these issues. Choosing these directions in research will help SMEs work with digital twins smoothly and effectively, which could make logistics operations more efficient (Lu et al., 2021).

9.0 Conclusion

DT technology is one of the potent possibilities for SMEs in the manufacturing industry to improve their logistics activities. Although several current implementations have focused on large companies, the report shows how SMEs can benefit. However, they exhibit weaknesses due to low technical capacity, financial resources, or incomplete digital infrastructure, which could hinder Digital Twin implementations, applying them in a step-by-step, progressive design. With well-defined logistics issues at the beginning and low-cost pilot programs, SMEs will achieve significant efficiencies in operations, inventory, and quality of delivery.

The results show that implementing DT can create measurable investment returns, such as up to 15 to 30 percent of the operational savings and better delivery lead time. Nonetheless, its success is closely tied to the preparation for its strategic action: organizations should invest enough in training; stewardship must be acquired, and the digital infrastructure allowing real-time data integration must be built. Also, in analysis, there are gender gaps in adopting new technology.

More specific support of women SMEs, causing greater access to funding, inclusion in training and mentorship initiatives when it comes to the digital transformation, should be considered to help women have equal access to that process.

The other significant dimension is sustainable. Digital twins will enable cutting carbon emissions, waste fewer resources, and enhancing energy use to make processes efficient and environmentally responsible. The future of SMEs is in logistics applications, and their gradual extension to production planning, predictive maintenance, quality products, and even customer experience simulation. Companies adopting this change earlier will be well-positioned to survive in the new reality of markets that get increasingly data-driven and thus competitive due to Industry 4.0.

10.0 Limitations of the Study

Methodological Limitations

Primary data were not used in the research, as the study used qualitative and secondary sources such as industry reports and published case studies. Such a method offers plenty of contextual information but fails to meet the statistical strength of large-scale quantitative studies. Also, the study lacks field or interview work, so the insight into operational challenges related to SMEs might be shallow.

Data Limitations

SMEs provided real-time or proprietary performance data in a limited way via DT—evidence from publicly available resources to depict in reporting based on success. Moreover, the insufficient evidence on gender-disaggregated data on technology adoption restricted the explorative approach to inclusive adoption strategies.

Generalizability

Applied to manufacturing SME and to logistical operations, the findings are primarily applicable in the high-income or digitalized areas. The framework, therefore, cannot entirely apply to SMEs in less-affluent or protracted resource locations without additional conditioning.

Future Research Directions

To further develop this work, it is necessary to:

Undertake an empirical study, such as longitudinal case studies or field experiments. To establish the cost-effectiveness of DT in SMEs and its functional implications.

Understanding how digital twins in logistics can be cross-sector and applied to other areas, including maintenance, quality inspection, and supply chain forecasting. Internationalize the study of inclusive adoption models, particularly those with women-owned and underserved SMEs that are much targeted. Discuss the contribution of DT to sustainability and the measure of decreased energy consumption, emissions, and wastes. Create digital maturity frameworks tailored to the SMEs based on size, industry, and digital capacity.

11.0 References

Abdullahi, S. M., & Lazarova-Molnar, S. (2025). On the adoption and deployment of secure and privacy-preserving IIoT in smart manufacturing: a comprehensive guide with recent advances. *International Journal of Information Security*, *24*(1). https://doi.org/10.1007/s10207-024-00951-8

Abideen, A. Z., Sundram, V. P. K., Pyeman, J., & Othman, A. K. (2021). Digital twin integrated reinforced learning in supply chain and logistics. *MDPI*, 5(4), 84. https://doi.org/10.3390/logistics5040084

Abolghasem, S., Carpitella, S., & Mohan, G. T. (2025). Digital twin implementation in small and medium size enterprises: a case study. In *Springer series in reliability engineering* (pp. 321–341). https://doi.org/10.1007/978-3-031-72636-1_16

Achouch, M., Dimitrova, M., Ziane, K., Karganroudi, S. S., Dhouib, R., Ibrahim, H., & Adda, M. (2022). On Predictive Maintenance in Industry 4.0: Overview, Models, and Challenges. *Applied Sciences*, *12*(16), 8081. https://doi.org/10.3390/app12168081

Achouch, M., Dimitrova, M., Ziane, K., Karganroudi, S. S., Dhouib, R., Ibrahim, H., & Adda, M. (2022). On Predictive Maintenance in Industry 4.0: Overview, models, and challenges. *Applied Sciences*, *12*(16), 8081. https://doi.org/10.3390/app12168081

Adesola, O., Taiwo, I., & Adeyemi, D. D. (2025). Leveraging digital twin technology for end-to-end supply chain optimization and disruption mitigation in global logistics. *World Journal of Advanced Research and Reviews*. https://doi.org/10.30574/wjarr.2025.25.1.0314

Alshahrani, M. A., & Salam, M. A. (2022). The Role of Supply Chain Resilience on SMEs' Performance: The Case of an Emerging Economy. *Logistics*, *6*(3), 47. https://doi.org/10.3390/logistics6030047

Banerjee, A. (2018). *Logistics industry - an overview | sciencedirect topics*. Www.sciencedirect.com. https://www.sciencedirect.com/topics/engineering/logistics-industry

Baxter, P. E., & Jack, S. M. (2016, January). *Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers*. ResearchGate. https://www.researchgate.net/publication/228621600_Qualitative_Case_Study_Methodology_Study_Design_and_Implementation_for_Novice_Researchers

Benjamin, Adegbola, E., Amajuoyi, N. P., Adegbola, D., & Adeusi, N. (2024). Digital transformation in SMEs: Identifying cybersecurity risks and developing effective mitigation strategies. *Global Journal of Engineering and Technology Advances*, *19*(2), 134–153. https://doi.org/10.30574/gjeta.2024.19.2.0084

Boudjemaa, Y. (2024, September 7). *Ensuring regulatory compliance in cloud-based big data systems: a framework for global operations adhering to GDPR and CCPA*. https://edgescholar.com/index.php/SKDISDA/article/view/e-2024-09-07

Burinskienė, A., & Nalivaikė, J. (2024). Digital and sustainable (twin) transformations: A case of SMEs in the European Union. *Sustainability*, *16*(4), 1533.

Caulfield, J. (2019, September 6). *How to do thematic analysis | step-by-step guide & examples*. Scribbr. https://www.scribbr.com/methodology/thematic-analysis/

Costa, A., Crupi, A., De Marco, C. E., & Di Minin, A. (2023). SMEs and open innovation: Challenges and costs of engagement. *Technological Forecasting and Social Change*, *194*(122731), 122731. https://doi.org/10.1016/j.techfore.2023.122731

Cremonini, C. E., Capela, C., Da Silva, A., Gaspar, M. C., & Vasco, J. C. (2025). Digital twin Integration for workforce Training: Transforming SMEs in the ornamental stone industry. *Systems*, *13*(2), 120. https://doi.org/10.3390/systems13020120

Cremonini, C. E., Capela, C., Silva, A. da, Gaspar, M. C., & Vasco, J. C. (2025). Digital Twin Integration for Workforce Training: Transforming SMEs in the Ornamental Stone Industry. *Systems*, *13*(2), 120–120. https://doi.org/10.3390/systems13020120

Crowe, S. (2017). The case study approach. *BMC Medical Research Methodology*, *11*(1), 1–9. NCBI. https://doi.org/10.1186/1471-2288-11-100

Dawadi, S. (2020). Thematic Analysis approach: a Step-by-Step Guide for ELT Research Practitioners. *Journal of NELTA*, *25*(1-2), 62–71. https://files.eric.ed.gov/fulltext/ED612353.pdf

De Marchi, M., Bonello, A., Francalanza, E., & Rauch, E. (2024). A Digital Twin for SMEs in the context of Industry 5.0. In *17th CIRP Conference on Intelligent Computation in Manufacturing Engineering (CIRP ICME '23)* (Vol. 126, No. 2024, pp. 242-247). Elsevier.

Dossou, P.-E., & Nshokano, C. (2023). Framework for Implementing Digital Twin as an Industry 5.0 Concept to Increase the SME Performance. *Lecture Notes in Mechanical Engineering*, 590–600. https://doi.org/10.1007/978-3-031-38165-2_69

Elbouzidi, A. D., El, A., Pellerin, R., Samir Lamouri, Estefania Tobon Valencia, & Marie-Jane Bélanger. (2023). The Role of AI in Warehouse Digital Twins: Literature Review. *Applied Sciences*, *13*(11), 6746–6746. https://doi.org/10.3390/app13116746

Enyejo, J. O., Fajana, O. P., Jok, I. S., Ihejirika, C. J., Awotiwon, B. O., & Olola, T. M. (2024). Digital Twin Technology, Predictive Analytics, and Sustainable Project Management in Global Supply Chains for Risk Mitigation, Optimization, and Carbon Footprint Reduction through Green Initiatives. *International Journal of Innovative Science and Research Technology (IJISRT)*, 609–630. https://doi.org/10.38124/ijisrt/ijisrt24nov1344

Forrester Consulting. (2023). *Advanced Manufacturing Report*. Hexagon. https://hexagon.com/advanced-manufacturing-report

Fortune Business Insights. (2024). *Digital twin market size, share, growth | analysis [2021-2028]*. Www.fortunebusinessinsights.com. https://www.fortunebusinessinsights.com/digital-twin-market-106246

Freight Amigo. (2025, April 17). *Case study: DHL's digital twin implementation - FreightAmigo*. FreightAmigo. https://www.freightamigo.com/blog/case-study-dhls-digital-twin-implementation/

Gennitsaris, S., Oliveira, M. C., Vris, G., Bofilios, A., Ntinou, T., Frutuoso, A. R., Queiroga, C., Giannatsis, J., Sofianopoulou, S., & Dedoussis, V. (2023). Energy Efficiency Management in Small and Medium-Sized Enterprises: Current situation, case studies and Best Practices. *Sustainability*, *15*(4), 3727. https://doi.org/10.3390/su15043727

GlobeNewswire. (2024). Supply Chain Digital Twin Market to grow at a CAGR of 12.0% Driven by the growth of the manufacturing sector globally. Retrieved from

https://www.globenewswire.com/news-release/2024/01/22/2812739/0/en/Supply-Chain-Digital-Twin-Market-to-grow-at-a-CAGR-of-12-0-Driven-by-the-growth-of-the-manufacturing-sector-globally.html

Graham, J. (2024, October 29). *What are the advantages of using iot sensors in building management? - planradar - HR*. PlanRadar - HR; PlanRadar – HR. https://www.planradar.com/au/advantages-iot-sensors-building-management/

Hana. (2025, May 16). *How AI is changing logistics & supply chain in 2025?* Docshipper.com. https://docshipper.com/logistics/ai-changing-logistics-supply-chain-2025/

Harris, L. (2024, November 26). *Telematics and big data: Revolutionizing fleet management in the automotive industry*. ResearchGate; unknown. https://www.researchgate.net/publication/386112807_Telematics_and_Big_Data_Revolutionizing_Fleet_Management_in_the_Automotive_Industry

Homayouni, S. M., Pinho, J., & Marques, C. M. (2024). Unlocking the potential of digital twins to achieve sustainability in seaports: the state of practice and future outlook. *WMU Journal of Maritime Affairs*. https://doi.org/10.1007/s13437-024-00349-2

Huang, Y., Ghadge, A., & Yates, N. (2024). Implementation of digital twins in the food supply chain: a review and conceptual framework. *International Journal of Production Research*, *62*(17), 1–27. https://doi.org/10.1080/00207543.2024.2305804

Iliuţă, M.-E., Moisescu, M.-A., Pop, E., Ionita, A.-D., Caramihai, S.-I., & Mitulescu, T.-C. (2024). Digital Twin—A Review of the Evolution from Concept to Technology and Its Analytical Perspectives on Applications in Various Fields. *Applied Sciences*, *14*(13), 5454. https://doi.org/10.3390/app14135454

Javaid, M., Haleem, A., & Suman, R. (2023). Digital twin applications toward industry 4.0: A review. *Cognitive Robotics*, *3*, 71–92. https://doi.org/10.1016/j.cogr.2023.04.003

Javaid, M., Haleem, A., & Suman, R. (2023). Digital Twin applications toward Industry 4.0: A review. *Cognitive Robotics*. https://doi.org/10.1016/j.cogr.2023.04.003

Kang, B. G., & Kim, B. S. (2024). Attachable IoT-based digital twin framework specialized for SME production lines. *International Journal of Simulation Modelling*, 23(3), 694. https://www.ijsimm.com/Full_Papers/Fulltext2024/text23-3_694.pdf

Kannan, S., & Gambetta, N. (2025). Technology-driven Sustainability in Small and Medium-sized Enterprises: A Systematic Literature Review. *Journal of Small Business Strategy*, *35*(1). https://doi.org/10.53703/001c.126636

Karaduman, Ö., & Gülhas, G. (2025). Blockchain-Enabled Supply Chain Management: A Review of Security, Traceability, and Data Integrity Amid the Evolving Systemic Demand. *Applied Sciences*, *15*(9), 5168–5168. https://doi.org/10.3390/app15095168

Kaya, F., Şanlı, E., Albayrak, Ö., Ünal, P., & Kirci, P. (2025). Asset Administration Shell Tool Comparison: A Case Study with Real Digital Twins Used in Petrochemical Industry. *Sensors*, *25*(7), 1978–1978. https://doi.org/10.3390/s25071978

Keelson, S. A., Cúg, J., Amoah, J., Petráková, Z., Addo, J. O., & Jibril, A. B. (2024). The Influence of Market Competition on SMEs' Performance in Emerging Economies: Does Process Innovation Moderate the Relationship? *Economies*, *12*(11), 282. Mdpi. https://doi.org/10.3390/economies12110282

Kharchenko, S., Morozova, O., Illiashenko, O., & Sokolov, S. (2020). A Digital Twin for the logistics system of a manufacturing enterprise using industrial IoT. *Information & Security: An International Journal*, 47, 125-134. https://doi.org/10.11610/isij.4708

Krishnan, R., Perumal, E., Govindaraj, M., & Logasakthi, K. (2024, March 4). *Enhancing Logistics Operations Through Technological Advancements for Superior Service Efficiency*. ResearchGate. https://www.researchgate.net/publication/378909954_Enhancing_Logistics_Operations_Through_Technological_Advancements_for_Superior_Service_Efficiency

Kshetri, N. (2021). *Amplifying the value of blockchain in supply chains*. Elsevier. https://www.sciencedirect.com/topics/social-sciences/digital-twin

Liu, H., & Faryaar, H. (2024, August 28). *Technology adoption is essential for improving businesses' growth, productivity, and competitiveness. This paper links two cycles (2017 and 2019) of the Survey of Innovation and Business Strategy with the Canadian Employer-Employee Dynamics Database to study the use of advanced and emerging technologies by women- and men-owned businesses in Canada.* Statcan.gc.ca; Government of Canada, Statistics Canada. https://www150.statcan.gc.ca/n1/pub/36-28-0001/2024008/article/00003-eng.htm

Liu, Y., Pan, S., & Ballot, E. (2024). Unveiling the potential of digital twins in logistics and supply chain management: Services, capabilities, and research opportunities. *Digital Engineering*, *3*, 100025. https://doi.org/10.1016/j.dte.2024.100025

Lu, Y., Liu, Z., & Min, Q. (2021). A digital twin-enabled value stream mapping approach for production process reengineering in SMEs. *International Journal of Computer Integrated Manufacturing*, *34*(7–8), 764–782. https://doi.org/10.1080/0951192x.2021.1872099

MarketsandMarkets. (2023, July). *Digital twin market size global forecast to 2026 | marketsandmarkets™*. Www.marketsandmarkets.com. https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html

Mashayekhy, Y., Babaei, A., Yuan, X.-M., & Xue, A. (2022). Impact of Internet of Things (IoT) on Inventory Management: A Literature Survey. *Logistics*, *6*(2), 33. Mdpi. https://doi.org/10.3390/logistics6020033

Matyi, H., & Tamás, P. (2021). Application of Digital Twin Technology in the Development of Logistics Process. *Advanced Logistic Systems - Theory and Practice*. https://doi.org/10.32971/als.2021.002

Mayorov, A. V., & Egorova, N. Y. (2024). Digital twins and their economically effective use in the logistics field. *Transport Technician: Education and Practice*. https://doi.org/10.46684/2687-1033.2024.2.173-178

Mchirgui, N., Quadar, N., Kraiem, H., & Lakhssassi, A. (2024). The Applications and Challenges of Digital Twin Technology in Smart Grids: A Comprehensive Review. *Applied Sciences*, *14*(23), 10933–10933. https://doi.org/10.3390/app142310933

Millers, M., & Gaile-Sarkane, E. (2021). Management Practice in Small and Medium-Sized Enterprises: Problems and Solutions from the Perspective of Open Innovation. *Journal of Open Innovation: Technology, Market, and Complexity*, *7*(4), 214. https://doi.org/10.3390/joitmc7040214

Moiceanu, G., & Paraschiv, G. (2022). Digital Twin and Smart Manufacturing in Industries: A Bibliometric Analysis with a Focus on Industry 4.0. *Sensors*, *22*(4), 1388. https://doi.org/10.3390/s22041388

Moshood, T., Nawanir, G., Sorooshian, S., & Okfalisa, O. (2021). Digital Twins Driven Supply Chain Visibility within Logistics: A New Paradigm for Future Logistics. *Applied System Innovation*, *4*(2), 29. https://doi.org/10.3390/asi4020029

Mousavi, Y., Gharineiat, Z., Karimi, A. A., McDougall, K., Rossi, A., & Gonizzi Barsanti, S. (2024). Digital Twin Technology in Built Environment: A Review of Applications, Capabilities and Challenges. *Smart Cities*, *7*(5), 2594–2615. https://doi.org/10.3390/smartcities7050101

Nagy, M., Figura, M., Valaskova, K., & Lăzăroiu, G. (2025). Predictive Maintenance Algorithms, Artificial Intelligence Digital Twin Technologies, and Internet of Robotic Things in Big Data-Driven Industry 4.0 Manufacturing Systems. *Mathematics*, *13*(6), 981. https://doi.org/10.3390/math13060981

Noyes, J., Booth, A., Moore, G., Flemming, K., Tunçalp, Ö., & Shakibazadeh, E. (2020). Synthesising quantitative and qualitative evidence to inform guidelines on complex

interventions: Clarifying the purposes, designs and outlining some methods. *BMJ Global Health*, *4*(1). NCBI. https://doi.org/10.1136/bmjgh-2018-000893

Ojeda, J. C. O., de Moraes, J. G. B., Filho, C. V. de S., Pereira, M. de S., Pereira, J. V. de Q., Dias, I. C. P., da Silva, E. C. M., Peixoto, M. G. M., & Gonçalves, M. C. (2025). Application of a Predictive Model to Reduce Unplanned Downtime in Automotive Industry Production Processes: A Sustainability Perspective. *Sustainability*, *17*(9), 3926. https://doi.org/10.3390/su17093926

Omowole, B. M., Olufemi-Phillips, A. Q., Ofodile, O. C., Eyo-Udo, N. L., & Ewim, S. E. (2024). Barriers and drivers of digital transformation in SMEs: A conceptual analysis. *International Journal of Scholarly Research in Science and Technology*, *5*(2), 019–036. https://doi.org/10.56781/ijsrst.2024.5.2.0037

Oteri, O. J., Onukwulu, E. C., Igwe, A. N., Ewim, C. P. M., Ibeh, A. I., & Sobowale, A. (2023). Cost optimization in logistics product management: Strategies for operational efficiency and profitability. *Journal not provided*.

Peretz-Andersson, E., Tabares, S., Mikalef, P., & Parida, V. (2024). Artificial intelligence implementation in manufacturing SMEs: A resource orchestration approach. *International Journal of Information Management*, *77*, 102781–102781. https://doi.org/10.1016/j.ijinfomgt.2024.102781

Rahmani, R., Jesus, C., & Lopes, S. I. (2024). Implementations of Digital Transformation and Digital Twins: Exploring the Factory of the Future. *Processes*, *12*(4), 787. https://doi.org/10.3390/pr12040787

Rahmani, R., Jesus, C., & Lopes, S. I. (2024). Implementations of Digital Transformation and Digital Twins: Exploring the factory of the future. *Processes*, *12*(4), 787. https://doi.org/10.3390/pr12040787

Rahmani, R., Jesus, C., & Lopes, S. I. (2024b). Implementations of Digital Transformation and Digital Twins: Exploring the Factory of the Future. *Processes*, *12*(4), 787. https://doi.org/10.3390/pr12040787

Rahmani, R., Jesus, C., Lopes, S. I. (2024). Implementations of Digital Transformation and Digital Twins: Exploring the Factory of the Future. *Processes*, 12(4), 787. https://doi.org/10.3390/pr12040787

Ramingwong, S., Sopadang, A., Tippayawong, K. Y., & Jintana, J. (2024). Factory Logistics Improvement: A Case Study Analysis of Companies in Northern Thailand, 2022–2024. *Logistics*, *8*(3), 88–88. https://doi.org/10.3390/logistics8030088

Ribeiro, E., Neto, A. A., & Nielsen, C. P. (2022). Digital Twins: Making It Feasible for SMEs. *Springer EBooks*, 343–348. https://doi.org/10.1007/978-3-031-15428-7_30

Roman, E.-A., Stere, A.-S., Roșca, E., Radu, A.-V., Codroiu, D., & Anamaria, I. (2025). State of the Art of Digital Twins in Improving Supply Chain Resilience. *Logistics*, *9*(1), 22–22. https://doi.org/10.3390/logistics9010022

Rrucaj, A. (2023). *Creating and sustaining competitive advantage in the Software As A Service (SaaS) Industry : best practices for strategic management*. Theseus. https://www.theseus.fi/handle/10024/814887

Sahin, O., Milisavljevic-Syed, J., Afy-Shararah, M., & Salonitis, K. (2025). Critical success factors in twin transition of SMEs toward digitalization and sustainability. In *Smart innovation, systems and technologies* (pp. 195–205). https://doi.org/10.1007/978-981-96-4459-9_18

Saka, R., Chinagozi, O. G., & Joe, O. N. (2023). Exploratory Research Design in Management Science: A Review of Literature on Conduct and Application. *International Journal of Research and Innovation in Social Science (IJRISS)*, *7*(4), 1384–1395. Researchgate. https://doi.org/10.47772/ijriss.2023.7515

Sharabati, A.-A. A., Ali, A., Allahham, M. I., Hussein, A. A., Alheet, A. F., & Mohammad, A. S. (2024). The Impact of Digital Marketing on the Performance of SMEs: An Analytical Study in Light of Modern Digital Transformations. *Sustainability*, *16*(19), 8667–8667. MDPI. https://doi.org/10.3390/su16198667

simul8. (2022). *CEVA Logistics use a simulation-powered digital twin*. Simul8 Simulation Software. https://www.simul8.com/case-studies/ceva-logistics-simulation-digital-twin?utm

Singh, M., Fuenmayor, E., Hinchy, E. P., Qiao, Y., Murray, N., & Devine, D. (2021). Digital Twin: Origin to Future. *Applied System Innovation*, *4*(2), 36. https://doi.org/10.3390/asi4020036

Tukamuhabwa, B., Mutebi, H., & Kyomuhendo, R. (2021). Competitive advantage in SMEs: effect of supply chain management practices, logistics capabilities and logistics integration in a developing country. *Journal of Business and Socio-Economic Development*, *3*(4). Emerald. https://doi.org/10.1108/jbsed-04-2021-0051

U.S. Small Business Administration (2022). *Small Business Profile: United States*. Retrieved from https://www.sba.gov/federal-contracting/contracting-guide

Werbińska-Wojciechowska, S., Giel, R., & Winiarska, K. (2024). Digital Twin Approach for Operation and Maintenance of Transportation System—Systematic Review. *Sensors*, *24*(18), 6069–6069. https://doi.org/10.3390/s24186069

Wu, D., Zheng, A., Yu, W., Cao, H., Ling, Q., Liu, J., & Zhou, D. (2025). Digital Twin Technology in Transportation Infrastructure: A Comprehensive Survey of Current Applications, Challenges, and Future Directions. *Applied Sciences*, *15*(4), 1911–1911. https://doi.org/10.3390/app15041911

Yasin, A., Pang, T. Y., Cheng, C.-T., & Miletic, M. (2021). A Roadmap to Integrate Digital Twins for Small and Medium-Sized Enterprises. *Applied Sciences*, *11*(20), 9479. https://doi.org/10.3390/app11209479

Yilmaz, G., Qurban, K., Kaiser, J., & McFarlane, D. C. (2023). Cost-effective digital transformation of SMEs through low-cost digital solutions. *IET Conference Proceedings.*, *2023*(16), 117–121. https://doi.org/10.1049/icp.2023.1742

Zaidi, S. A. H., Khan, S. A., & Chaabane, A. (2024). Unlocking the potential of digital twins in supply chains: A systematic review. *Supply Chain Analytics*, *7*, 100075. https://doi.org/10.1016/j.sca.2024.100075

Židek, K., Piteľ, J., Adámek, M., Lazorík, P., & Hošovský, A. (2020). Digital Twin of Experimental Smart Manufacturing Assembly System for Industry 4.0 Concept. *Sustainability*, *12*(9), 3658. https://doi.org/10.3390/su12093658