A Systematic Exploration of Critical Applications for Digital Twins in Supply Chains Logistics and their Enabling technologies

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Digital Twin (DT) technology has emerged as a transformative solution at a time where global supply chains are highly interconnected and are facing increasing disruptions, shortcomings, and sustainability challenges. Digital Twins help mitigate these inefficiencies by offering various services such as real-time monitoring and predictive analytics for logistics operations. It provides these services by creating a virtual replica of the physical systems. This study conducts a systematic literature review to identify the most critical applications and enabling technologies of DTs in logistics. The research unifies numerous findings into a single, comprehensive analysis, providing DT developers and stakeholders with a unified perspective on the most critical technologies and applications in a single location. By offering a consolidated view, this research enhances understanding and provides a foundation for further exploration of DT's potential to transform supply chains logistics into resilient, efficient, and sustainable systems.

Additional Key Words and Phrases: Digital Twins, Logistics, Technologies, Applications, Systematic Literature Review

1 INTRODUCTION

Global supply chains are highly susceptible to a wide range of challenges, including positive challenges such as technological advancements and negative challenges caused by natural or human-made disasters. The 21st century has already witnessed the transformative effects of Industry 4.0 as a technological revolution, as well as the disruptive consequences of a global pandemic like COVID-19 and the blockage of the Suez Canal [11][15][8]. These challenges highlight the vulnerability and interdependence of modern-day supply chains, emphasising the necessity for systems that are capable of adapting to uncertainties while preserving efficiency in a volatile global environment.

Digital Twin technology has emerged as a transformative tool for supply chain resilience, offering real-time replication of physical supply chains in a digital environment. This allows stakeholders across the supply chain to monitor operations, predict disruptions, and optimize performance dynamically. However, building a Digital Twin for logistics requires the integration of various technologies, including IoT, AI, and blockchain. Despite the potential of DT, DT stakeholders and DT developers often face uncertainty about the technological requirement, their applications, and the tangible outcomes of developing a DT. This lack of clarity hinders informed decision making and slows the adoption of DT in various industries.[16]

This thesis addresses this gap by conducting a systematic literature review to identify the critical technologies enabling Digital Twin implementation in logistics and to explore their applications. The findings aim to provide stakeholders with an overview of the technological requirements and potential benefits of investing in Digital Twin solutions, empowering them to make informed decisions for building resilient and efficient supply chains, and serve as a foundational research study for future researchers.

2 RESEARCH QUESTION

In order to address this research, the paper aims to answer the following question: *"What is the current literature landscape about Digital Twins in the logistics sector?*

In order to answer the research question, the main research question is divided into three sub-questions, each delving into a fundamental aspect of the digital twin.

(1) What are the different frameworks of a Digital Twin in the logistics sector?
(2) What are the principal applications of Digital Twins in logistics?
(3) What are the key enabling technologies for the development of Digital Twins in logistics systems?

This study focuses on the logistics sector, examining the components of Digital Twins, their applications, and the technologies that facilitate their deployment. The study focuses on generic applications and enabling technologies in order to establish a foundational work.

3 METHODOLOGY

The study adopted the systematic literature guidelines proposed by [14] for a structured approach to identify and evaluate the relevant literature. An SLR is a structured and thorough research method that is used to collect, analyse, and incorporate all relevant studies on a specific topic. The SLR is designed to address the research questions mentioned in section 2.

The literature search was conducted across various academic databases such as *Scopus, Web of Science, IEEE Xplore* and *Science Direct*. These databases were selected for their comprehensive coverage of scientific and technical literature relevant to the research question. The search will use the query constructed with the keywords derived from the research question.
(("Digital Twin" OR "Digital Twins") AND "logistics" AND (("Technolog*") OR application*))
The results of the above query across the four databases resulted in a substantial amount of papers concentrating on manufacturing and other areas of the supply chain. The search was then refined by restricting the query to titles, keywords, and abstracts. The query resulted in 846 articles.

To ensure the relevance and the quality of the studies resulted from the search, the following inclusion and exclusion criteria were

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applied:

Inclusion Criteria

(1) The study must discuss Digital Twins within the logistics domain.
(2) The study must be focused on frameworks, applications, enabling technologies of Digital Twins.
(3) The study must be peer-reviewed to ensure academic standards and must be either a journal article or conference paper.
(4) The study must be published in English.
(5) The study must be published between 2015 and 2024; foundational work will be included. (DT gained considerable growth post 2015, driven by advancements in IoT, AI and Industry 4.0 so in order to keep the study up to date and in accordance with the new discoveries the timeline of 2015-2024 was chosen)

Exclusion Criteria

(1) The study is incomplete, or restricted.
(2) The study is not focused on Digital Twin in logistics but in other applications like manufacturing, healthcare,etc.
(3) The study is to be paid for.
(4) The study is duplicate, in which case the most complete version will be maintained.

After applying the search strategy, inclusion criteria and exclusion criteria, a backward snowballing as proposed by [22] was applied to ensure the inclusiveness of the relevant studies. Backwards snowballing refers to process of identifying additional relevant studies by reviewing the reference lists of the studies that are selected. The articles were then screened based on the title and abstract to remove irrelevant studies and assess the relevance of the other articles. Finally, after the screening process, a total of 24 articles were selected for the full analysis. The selected papers captured different segments of the logistics domain and can help answer the research question from different perspectives.

Figure 1 provides the visual representation of the step-by-step selection process adopted in the SLR.

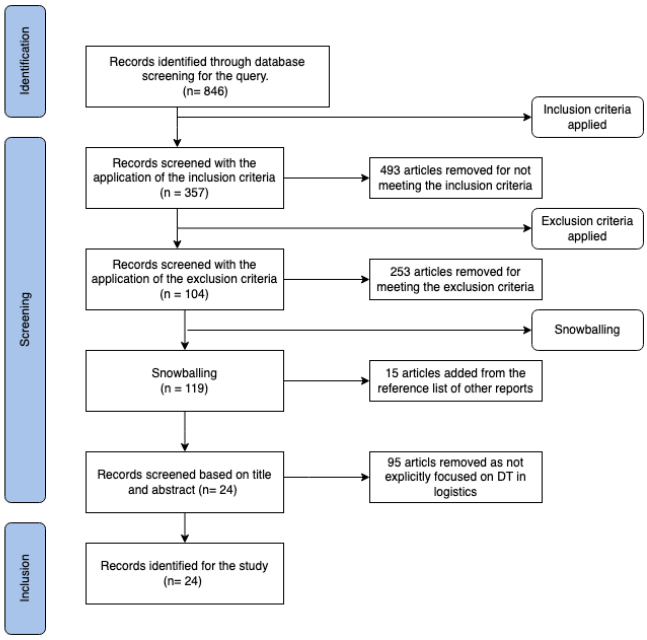

Fig. 1. Selection Process

4 FINDINGS AND DISCUSSIONS

4.1 Overview of digital twin

Initially developed by NASA to monitor spacecraft systems, the concept of DTs has evolved far beyond aerospace applications. Today, DTs are employed across diverse industries, including manufacturing, healthcare, and logistics. They are transforming key areas such as warehouse management, production planning, transportation management, supply networks, and many more in the logistics sector. Digital Twins create virtual representations of physical assets, systems, or processes, allowing real-time synchronization between digital and physical domains. Leveraging cutting-edge technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and advanced simulations, DTs offer unparalleled capabilities in monitoring, predicting, and optimizing logistics operations.

The logistics sector is a crucial part of the global supply chains, it enables the seamless flow of raw materials, goods, and finished products worldwide. In an environment of increasing complexity, demands for sustainability, and challenges in maintaining resilience, the supply chain is at a high risk of disruption frequently. By enabling logistics operators to predict potential disruptions, optimize delivery routes, and monitor the condition of goods in real time, DTs enhance operational efficiency and significantly reduce costs. The logistics domain within the supply chain can be segmented into two broad categories[5, 16, 19]:

- *First-Mile-Transportation*- It is defined as the transportation of goods from suppliers or manufacturers to distribution centres.
- *Last-Mile-Delivery*- It is the transportation of goods from the distribution centres to the end customer. It is also known as city logistics or urban freight distribution.

Along with these there are other segments that are also within the logistics domain.They are *intra-logistics* which refers to the storage and movement of materials within facilities [16] and *supply Network* which is the collaboration and alignment among various entities within the logistics network. [16].

The essential characteristics of a Digital Twin for Logistics (DTL) are: [5, 6, 19]

- Timely - Timeliness allows the system to respond appropriately to operational needs, with flexible data update frequencies tailored to the criticality of each use case, balancing real-time responsiveness with resource efficiency.
- Bidirectional - Bidirectional exchange enables continuous synchronization between physical and virtual entities, ensuring that changes in the physical realm inform virtual simulations, while actionable insights from the virtual model improve physical operations.
- Long-term - Long-term design supports the sustained value of DTLs by creating a digital thread that tracks the lifecycle of assets and processes, enabling traceability, scalability, and adaptation to evolving logistics requirements.

These characteristics ensure the adaptability and efficiency of DTLs in dynamic logistics situations. Together, these characteristics make DTLs robust, interactive, and future-proof solutions for managing complex logistics networks. [5, 8, 19]

4.2 Comparative Analysis of Digital Twin Frameworks

Digital Twin in logistics essentially comprises of three interlinked layers[2, 15, 17, 23], the **physical layer** comprises of tangible assets like vehicles, warehouses, and IoT sensors, which collect data from real-world operations, the **communication layer** bridges the physical and digital layers and ensures secure and seamless data exchange in real time. the **digital Layer** processes collected data into actionable insights using predictive analytics and simulation tools.

Multiple researchers including [15] and [23], underscore these three layers as the foundational layers for scalable and modular DT systems. These layers operate in a closed loop to perform seven essential processes that enable the seamless operation and utility of DTs in logistics and supply chains - *Sampling, Storage, Modelling, Simulation, Learning, Prediction, Actuation.*

Digital Twin can be applied to various logistics cases such as global supply chain, multimodal transportation, urban logistics, etc. The foundational model provides a versatile blueprint for the various logistics cases that can be adapted and extended to address specific logistical challenges.

This section compares four frameworks developed for different logistics scenarios by analysing the modifications made to them, the motivations behind these modifications and and their outcomes. The discussion is summarized in Table 1.

1. The 5-PL Framework [19] was developed for fifth-part logistics providers. It focuses on global, multi-stakeholder operations that require real-time synchronisation and collaboration. In order to meet these requirements, firstly, the framework introduces **connections** that incorporates links and threads to enhance real-time synchronisation across geographically dispersed assets and secondly, it introduces **blockchain** to provide secure and immutable data-sharing capabilities and enhance transparency. These modifications were done in order to address real-time changes like disruptions, demand fluctuations, or route optimisations and enhance collaboration and trust among the multiple stakeholders involved in global supply chain. The modifications provide real-time integration and data analytics to improve operation efficiency and the framework also provides logistics managers with the tools for scenario modelling, risk prediction, etc.

2. The DSCT framework for Multimodal Supply Chain [6] addresses the complexities of a multimodal logistics network. The **Supply Chain Model** module is the core of the framework and is responsible for replicating the physical supply chain. This is complemented by the **Interface Module**, which integrates data from various sources and blockchain, ensuring secure and interoperable data sharing. The framework further incorporates **Optimization** and **Simulation Models** to enable predictive analytics and "what-if" scenario evaluation. These modifications are done in order to address several challenges that are common in multimodal supply chains such as lack of transparency and visibility, difficulty in managing disruptions. Modifying the foundational framework to the five module framework enhances data integration and analysis capabilities providing real-time visibility and proactive risk management. It enhances resilience by predicting disruptions and enabling dynamic responses. The DSCT framework enhances collaboration and performance within complex logistics networks.

3. The Digital Twin Framework for Adaptive Last Mile City Logistics [4] is designed to address the unique challenges of urban logistics. The modifications are the **Data and Model Management** and **Decision System**. The Data and Model management layer analyses the data collected by the physical layer to simulate urban logistics scenarios, while the Decision Systems facilitate dynamic policy development, including the optimisation of delivery routes and the implementation of low-emission zones. The motivation lies in the growing demand of urban logistics, driven by the rise of e-commerce, urbanisation. The urban areas often face challenges such as traffic congestion, elevated emissions, etc. The framework helps mitigate these challenges through the optimisation of delivery routes and the balancing of urban logistics flows. The Adaptive Last Mile Framework provides a scalable and sustainable approach to the increasing complexities of urban logistics.

4. The 7-Element Framework [10] extends the foundational model by integrating socio-technical aspects namely **People, Management, Organisation.** The framework address the complexities of integrating DT into logistics and supply chain operations by synchronising technological systems with human and organisational elements. This framework is designed to enhance stakeholder participation, organisational cooperation, and scalability, it guarantees that digital twin solutions are both technologically sophisticated and practically applicable within the current workflow. These modifications

Table 1. DT Frameworks

Framework	Logistics Scenario	Purpose	Layers
5 PL Framework [19]	Fifth Party Logistics	Enhance collaboration and enable real-time synchronization	Physical Entities Virtual Entities Services Data Connections
DSCT Framework [6]	Multimodal Logistics Networks	Improve visibility and transparency	Supply Chain Module Interface Module Simulation Module Optimisation Module Reporting Module
Adaptive last Mile Framework [4]	Urban Logistics	Urban logistics challenges like congestion, emissions	Physical Data/Model Management Decision Systems
7-element Framework [10]	Supply Chain and Operations managers	Provides a holistic, socio-technical perspective	Technology People Management Organisation Scope Task Modelling

allow for better decision making and greater applicability across various logistics scenarios.

4.3 Applications of Digital Twins in Logistics

There are numerous applications of digital twins across the supply chain. [8] divides the five application areas of DSCT on two levels: *Network Level, Site Level*. Network level comprises of network management and transportation and site level comprising of manufacturing, warehousing, and cargo handling. [16] mentions through the study that multiple authors have identified various applications and services of DT, however, the requirements for a logistics and supply chain system are different. These are eight most critical DT-enabled applications in Logistics Supply Chain Management:

Monitoring - Visualization of the different physical objects, systems, process through a digital twin. This process helps in ensuring real-time synchronization, maintain data accuracy and quality to make informed decisions.
Evaluation - Analysing the performance of current operations or systems and testing potential future capabilities through simulation.
Prediction - Analysing historical data and integrating it with real-time data to anticipate future actions. It can be achieved through methods such as machine learning or simulation.
Optimization - Enhance operational decision-making through expert evaluations, simulations, or mathematical modelling based on the observed state and possible changes in the status of digital twins.
Control - Seamless integration between the physical and the virtual counterparts. It ensures effective implementation of the decisions in the virtual environment to the real world.
System management - Creating digital representation of tangible assets such as infrastructure, machines and intangible assets such as data to form an integrated and synchronized system.
System Integration - Collaboration and co-ordination of various stakeholders by connecting multiple Cyber-Physical Systems to enable global optimisation.
Adaptation - Ability of the DT to adjust its action based on its data , current situation, system status, etc.

4.3.1 Digital twin enabled services and applications. This section will delve deeper into the above mentioned services of DT in logistics sector:
Monitoring,[16] highlights the enhancement of transport security by monitoring hazardous chemical waste. [7] highlights the integration of blockchain with DT for enhancing cargo monitoring, offering a decentralised data storage ensuring reliability and transparency in cargo tracking systems. In marine logistics, digital twins facilitate cargo monitoring, providing real-time information and reducing risks [25]. In [1] and [26], real-time oversight of orders, resources, and processes enable decision makers to identify anomalies and deviations in planning, thereby ensuring efficient responses and system stability. Likewise, [17] emphasises structural health monitoring in bridge projects, where real-time sensor data enhances safety by forecasting potential failures, while [18] highlights the monitoring of warehouse conditions such as temperature and humidity to maintain the quality of cold-chain products. According to [8, 16, 23, 26], DT in production logistics enable real-time monitoring and data processing for AGVs (Automated Guided Vehicle) routing and material distribution optimisation.

Evaluation - In[16] and [6], digital twins facilitate the simulation of "what-if" scenarios in logistics and multimodal supply chains, evaluating the impact of disruptions and identifying optimal configurations to improve resilience and predictive planning. Also, [18] and [1] focus on the potential of DT for assessing cold chain logistics, to enhance operational efficiency. In urban and sustainable logistics,[21] illustrates how simulation evaluate ecological and economic effects, facilitating decision-making for enhanced, sustainable urban transportation systems. In [23] and [3], the papers emphasises on developing effective risk management strategies using the simulations of disruptions with the integration of ERPs and BI systems. The [26] paper highlights the use of simulations to evaluate and optimise the operational processes, eliminate bottlenecks and synchronise operations with key performance indicators in internal logistics.

Prediction services improve supply chain resilience, [6] mentioned the possibility of predicting delivery times, bottlenecks in the supply chain. In maritime logistics, [25] highlighted the potential to DT to predict the occurrence of future waves and ship reaction, lowering the risk and fuel usage of the ship. In [4], different ML techniques are used to predict optimal routes for delivery based on several factors such as fees on low emission zones. DT can be used to identify and reduce risks by forecasting possible issues such as supply chain disruptions, modular construction transport, accidents during hazardous chemical transport [16].

Optimisation - [16] emphasises dynamic decision-making via machine learning techniques, simulation methods, and optimisation algorithms, facilitating route optimisation in urban deliveries, warehouse layout efficiency, and efficient optimisation for resilient supply networks. Similarly, [3] highlights the incorporation of real-time data with simulation models for strategic planning in network design, inventory management. [1] focuses on optimising resource allocation and transport scheduling to reduce bottlenecks and improve system performance. [10] mentioned preventive maintenance and dynamic scheduling, ensuring supply chain resilience and resource efficiency. [8] illustrates optimisation in route planning, material handling, cargo handling, and warehouse operations.

Control - Digital twins manage temperature, humidity, and air velocity in cold chains, preserving product quality and prolonging shelf life[16]. [1] emphasises the combination of real-time data with simulation logic to dynamically manage logistics resources and operations. This method minimises discrepancies, optimises resource utilisation, and improves overall system dependability by adjusting to real-time circumstances. In [20], ERP systems like SAP's vehicle maintenance and dispatch solutions use real-time analytics to facilitate operational planning for trains and vehicles. This bidirectional feedback loop guarantees synchronisation between real assets and virtual twins, preserving operational safety and efficiency. Lastly, [19] highlights control for real-time alerts for disruptions enable immediate adaptation to changes in logistics operations, supporting continuous operational improvements and enhancing service quality.

System Management - In [4], Digital Twins form an integrated urban logistics systems by integrating tangible and intangibles assets and help in enabling adaptive policies for sustainable last-mile deliveries and improved resource allocation and minimise environmental impacts. Similarly, in [6] integration of physical supply components with digital twins improved transparency and operational efficiency by aligning multimodal transportation system. Incorporating both physical and intangible assets enhanced the decision making by providing real-time monitoring and predictive insights into operational processes [16]. The real-time integration of simulation tools with operational data for dynamic logistics network management has optimised resource utilisation and transportation schedules, diminished operational inefficiencies, and facilitated predictive capabilities for proactive system modifications [1].

System Integration - The usage of blockchain and Web3 technologies to securely integrate DTs across distributed supply chain provided a secure, immutable platform for collaboration among stakeholders, ensuring data integrity [6, 9]. The integration enhanced the coordination among various subsystems and stakeholders and improved transparency, optimisation of logistics workflows [12, 13, 16, 18].

Adaptation - DT identifies and adapts to disruptions, such as equipment malfunctions or unexpected delays, by reallocating resources or rerouting ship, reducing delays, and optimising resource utilisation, etc[25]. DT tracks emissions, fuel consumptions, and energy usage enabling the companies and stakeholders to adjust operations dynamically [21, 25]. DT adapt logistics processes based on real-time data improving supply chain resilience, ensuring efficient coordination [6, 12, 18, 23].

These are the eight most critical services of a DTL enabling various applications for the optimisation of the supply chain logistical challenges.

4.4 Technologies of Digital Twins in Logistics

Digital Twin implementation relies heavily on a strong technical foundation. In order to facilitate the above mentioned applications and services a digital twin must be equipped with all the relevant and foundational technologies to provide revolutionary value in logistics and supply chain by enabling real time monitoring, powerful modelling and simulation, predictive analytics and many more. Therefore, it is very essential to identify the critical technologies. Table 2 provides an brief overview of the critical applications of a logistics digital twin and the enabling technologies along with examples of the use cases. It serves as an comprehensive overview derived from the study highlighting the alignment between the applications of DT and their technological requirements.

This section examines the essential technologies that are needed to develop a digital twin for logistics, emphasising their functions in facilitating crucial applications such as monitoring, prediction, optimisation. According to [19], the framework for a logistics digital twin should categorises the value creation of DTL use cases into five types:

Table 2. DT applications with their associated technologies

Applications	Technologies	Example
Monitoring	IoT Sensors, RFID, Wireless Communication	Asset Tracking, Cargo conditions monitoring, warehouse monitoring for temperature humidity
Prediction	Predictive Models, Machine Learning, Artificial Intelligence, Neural Networks, Deep Learning Algorithms	Delivery delays, Bottlenecks, Disruptions, predicting optimal routes or ship reactions
Evaluation	Machine Learning Models, Cloud Computing, Simulation Platforms	Simulating "what-if" scenarios, urban logistics
Optimisation	Optimisation Models, Simulation Tools, Double layer Q-learning, Dynamic Optimisation Algorithms	Improving warehouse layouts, route optimisation for urban deliveries, dynamic scheduling
Control	ERP systems, Dynamic Resource Management	Real-time operation management
System Management	Blockchain, Cloud Computing, Cloud Storage, Edge Computing	Integration and synchronisation between assets, processes and systems
System integration	Blockchain, Web3 Technologies	Trusted and transparent collaboration among stakeholders, End to End visibility
Adaptation	Scenarios Analysis platform, Real time monitoring, Decision Support Systems	Enabling real time adjustments, optimising emissions tracking, reallocating resources

(1) *Descriptive* - Effectively visualize the outline asset status enabling the access to interpret remote and critical information.
(2) *Analytical* - Use analytics for obtaining critical insights which cannot be done otherwise.
(3) *Diagnostic* - Identify the main causes of logistics issues using analytics, ML, etc.
(4) *Predictive* - Forecast the future behaviours with precision and accuracy.
(5) *Prescriptive* - Make decisions and take the corrective measures based on predictions.

These five value creation use cases align seamlessly with the applications and services necessary for a Digital Twin in logistics such as monitoring, prediction, etc, establishing the basis for identifying the technological requirements for DTL. In order to address these value-driven use cases Logistics Digital Twin must integrate technologies that facilitate the implementation of these essential functions. This ensures DTL's technological infrastructure is well suited to support and enhance related applications and services, thus improving efficiency, adaptability, and resilience in logistics operations. Similarly, [16] also mentions the five key capabilities a digital twin must include in order to deliver the the previously mentioned services. The five key capabilities are: *(1)Integration, (2)Computation, (3)Simulation, (4)Interoperation, (5)Evolution.* According to [7], a digital must be composed of four pillars: *data acquisition and management, modelling the reality, simulation and forecasting, presentation and visualisation.* Finally, [15] also mentions that a DT must be equipped with these seven processes in order to enable all the DT functionality (applications and services): *sampling, storage, modelling, simulation, learning, prediction, and actuation.* The similarity in requirements for a digital twin in logistics across different literature helps to establish that the seven processes mentioned by [15] are essential in order to facilitate the critical services of DT as these support the operation a digital twin ensuring the delivery of the services mentioned by [16].

4.4.1 *Technologies based on DT capabilities.*

(1) **SAMPLING** - Sampling is the first step in digital twins, Data is collected from tangible and intangible assets which enable various DT-enabled services. **IoT devices** are key enablers for supply chain visibility by continuously collecting data which is used for various other services of the digital twin [2, 8, 25]. In cold chain logistics, they enable real-monitoring for temperature, humidity, and air quality to maintain the product quality during transportation.[7, 16, 23]. IoT also improves on-time delivery and food freshness [15] and help to synchronise real-time data inputs [15]. IoT devices are used to track assets such as trucks and collect real time data on the state of the assets reduce and prevent possible failures [7]. IoT devices provide real-time data integration, enhancing dynamic decision-making in logistics operations via actionable insights and intelligent changes[9]. **RFID** is another wireless technology used to collect real time data, it improves the tracking and tracing of goods and shipments across the supply chain, offering real-time information [6, 13, 15]. RFID technology is especially effective in warehouse operations where it helps to automate inventory management which reduce manual efforts [3, 16]. Sensors integrated into logistics equipment continuously gather data to forecast probable problems, allowing proactive measures to reduce downtime and ensure operational continuity [1].

(2) **STORAGE** - Storage is an essential part of DT development, it lays the foundation for other DT applications such as optimisation, prediction. It is important to efficiently and safely

store vast amounts of data collected by the various process, assets, and systems. **Cloud based Systems** are the most preferred way of data storage in majority of the literature. These systems provides a central storage hub for static and dynamic operational data, supporting real-time updates and historical data [3, 11, 19] and scalability [13, 17]. **Cloud computing** provides computational power to simulate supply chain scenarios [3, 10, 20, 21]. **Cloud storage platforms** like AWS, Google cloud, or Azure has been suggested by multiple papers [8, 12, 15] for scalable and resilient storage. **Edge computing** was another technology mentioned for localised data processing and in order to reduce latency and ensure timely updates to digital twins, particularly in areas requiring constant real-time decision making such as warehouse and transportation hubs [9, 15, 26]. Few authors suggest a data standardisation protocol to help integrate different systems and enhance end-to-end visibility like the EU's eETI regulation [8, 16]. **Blockchain technology** is progressively being combined with digital twin systems to improve the security and immutability of stored data. Blockchain guarantees that all transactions and modifications inside the digital twin ecosystem are traceable and immutable, making it advantageous, especially, in multi-stakeholder contexts such as supply chain logistics [7, 9, 16].

(3) **MODELLING** - Modelling refers to the replication of physical systems in virtual environments. These replicas then help to simulate, analyse and optimise logistics and supply chain operations. There are various types of models mentioned in the literature. **Machine Learning** models are the most frequently mentioned model. These models are used for analysing patterns, predictive analytics, and decision making. These models enable predictive analytics such as forecasting demand, predicting disruptions. These also enable the digital twin to detect anomalies in the supply chain and help with different kinds of optimisation [1, 8, 16, 18]. **Agent-based models** are widely used to simulate interactions between individual entities in logistics [3, 6, 15]. In last mile logistics, agent based models are used for route planning, delivery planning [26]. **Behavioural models** are used to assess the relationship between stakeholders [4, 12, 16]. **Predictive models** are designed to forecast future outcomes like disruptions, demand, etc. based on real time and historical data stored in the clouds [16, 21]. In [24], predictive models help analyse how safety measure work and identify potential challenges before then happen. **Physical models** provide representation of physical assets in the logistics network and enable asset monitoring for predictive maintenance [25] in order to avoid delays. **Optimisation models** are very essential for maximising efficiency and improving the overall process and system[1, 11]. In [6], optimization models are used for efficient route planning, maximising carrier utilisation, etc.

(4) **SIMULATION** - Simulation within digital twins is essential for the analysis, prediction, and optimisation of supply chain operations. It facilitates "what-if" scenario analysis to assess the effects of various strategies, disruptions, and operational modifications, which helps to promote informed decision-making. **Discrete Event Simulation** is commonly employed to model logistics events, including loading, unloading, and transport delays. Discrete Event Simulation facilitates comprehensive analysis of operational processes, enabling the identification of bottlenecks and the evaluation of resource allocation strategies [1, 13]. **Continuos Simulation** can facilitate real time optimisation, prediction for systems that continuously change such as fuels consumption in [6], temperature, cargo conditions [15], etc. Simulation platforms like AnyLogic, Simio, and MATLAB are frequently referenced for their capabilities in creating flexible and scalable models for supply chain operations. These platforms integrate with digital twins to provide virtual experimentation environments, which are critical for testing logistics policies and new technologies without physical disruptions[6, 19]

(5) **LEARNING** - Learning in digital twins focuses on extracting insights from historical and real-time data to enhance decision-making, optimize operations, and predict future events. **Machine Learning** and **Artificial Intelligence** both play a crucial role in this process, allowing digital twins to adjust to changing environments and enhance performance over time. Machine Learning techniques are extensively utilised for predictive maintenance, demand forecasting, and route optimisation. **Neural networks** and **reinforcement learning** models analyse large amounts of data to detect patterns, anomalies, and areas for improvement [1]. **Deep Learning** algorithms, including long short-term memory networks, are employed for time-series forecasting, allowing digital twins to anticipate supply chain trends and disruptions [15, 16, 23]. **Federated Learning** represents an innovative method for collaborative model training among various stakeholders while maintaining data privacy. This approach enables decentralised systems to exchange insights while maintaining control over sensitive data, thereby improving the resilience of digital twin applications in environments with multiple stakeholders [9, 19]. Learning models that incorporate digital twins undergo continuous refinement through feedback loops. **Self-learning algorithms** adjust system parameters, including inventory thresholds and delivery routes, based on real-time data, thereby ensuring ongoing system optimisation. Predictive analytics engines integrate historical data with machine learning outputs to forecast potential risks, including supply chain bottlenecks and equipment failures, thereby enabling proactive mitigation.

(6) **PREDICTION** - Prediction in digital twins are focused on forecasting future states, identifying risks, and optimizing decision-making by utilising real-time data and advanced analytics. Predictive models integrated with digital twins enable supply chain managers to anticipate disruptions, improve the overall operational efficiency, and enhance resilience. **Predictive Analytics Engines** are widely employed to forecast demand, inventory requirements, and transportation delays.

For instance, machine learning models analyse historical and real-time data to identify patterns, trends, and anomalies, enabling proactive adjustments to logistics operations. Dynamic optimization models support adaptive decision-making by evaluating real-time supply chain changes and recommending optimal strategies [6, 9, 15]. **Scenario-based prediction** is another critical aspect, allowing digital twins to evaluate potential outcomes of various logistics strategies. By simulating different scenarios, such as demand surges, supply disruptions, or environmental changes, digital twins provide insights into the best courses of action under uncertain conditions [1, 19]. Several authors highlight the role of cloud-based platforms in supporting predictive analytics. Cloud systems provide the computational power required for training and deploying predictive models, ensuring scalability and accessibility for global supply chain operations [8, 12].

(7) **ACTUATION** - Actuation in digital twins emphasises the implementation of real-time modifications and the execution of decisions based on predictive analytics, simulations, and dynamic data inputs. **Decision Support Systems** frequently integrate actuation capabilities to deliver actionable insights for human operators. Dashboards associated with digital twins display real-time KPIs and suggested actions, allowing supply chain managers to make informed decisions or approve automated responses. Actuators enabled by the Internet of Things are essential for implementing real-time modifications in logistics operations. Actuators incorporated into warehouse systems can modify conveyor speeds, sorting mechanisms, and storage conditions in real-time, utilising data from digital twins. Actuators in cold chain logistics regulate refrigeration systems to sustain optimal temperature and humidity, thereby preserving product integrity during transportation [1, 15, 16, 23].

5 CONCLUSIONS

This section addresses the findings of the study to answer the research questions mentioned in Section 2 and conclude the study.

This thesis systematically examined the critical applications of Digital Twin (DT) technology in logistics and supply chain management, focusing on core capabilities such as sampling, storage, modelling, simulation, learning, prediction, and actuation.

Q1. What are the different frameworks of a Digital Twin in the logistics sector?
The study identified a **foundational framework** for digital twins in logistics, comprising of three layer: Physical, Communication and Virtual. The study also identified that there is no single framework that fits all. Instead, there are multiple framework, each catering to different logistics segments, business objectives, etc. To establish this the study compared four different framework from different logistics segments and identified the modifications made to them, the motivations behind these modifications and the result of the modification. The study compared the 5-PL framework, the DSCT framework, the urban logistics framework, the 7 element framework [4, 6, 10, 19]. The study revealed for instance, the frameworks designed for global supply chain focus on real-time monitoring and prioritise stakeholder collaboration and data synchronisation and those for urban logistics prioritise environmental sustainability and last-mile delivery optimisation[4, 6].

Q2. What are the principal applications of Digital Twins in logistics?
Numerous papers discuss the various applications of digital twins. Each logistics domain prioritises certain applications above others. The paper identified the core applications of digital twin. [16] highlights the diverse applications of DT across different areas. The logistics DT has different critical applications compared to a DT focused on manufacturing. The study highlights the eight DT twin enabled services which are critical for a digital twin in the logistics sector. The eight DT applications are: **Monitoring, Evaluation, Prediction, Optimisation, Control, System management, System integration, Adaptation**.

Q3. What are the key enabling technologies for the development of Digital Twins in logistics systems?
The study synthesized the key enabling technologies the fulfil the seven process mentioned by [15] and facilitate the DT applications mentioned above. The critical enabling technologies are: **IoT, RFID, Cloud Computing, Blockchain, Machine Learning, Artificial Intelligence, Simulation Tools, Decision support systems.**

6 LIMITATIONS

This study, although thorough, presents few limitations. The study failed to conduct a extensive and rigorous quality assessment for the selected papers. The focus on generic applications restricted insights into particular domains, and the results lack empirical validation via real-world case studies. The identified limitations indicate some possible directions for future research aimed at improving and extending the findings of this study.

7 FUTURE WORK

Subsequent research need to concentrate on domain-specific applications of Digital Twins (DTs) in sectors such as marine logistics or cold chains, with the addition of new technologies like 5G and quantum computing. Investigating socio-technical aspects, performing empirical validation via case studies, and examining environmental sustainability are essential subsequent actions.

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