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Article

Digital Twins for Real-Time Operations Monitoring and Optimization in Oman's Logistics Sector

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Abstract: Digital twins (DTs) are transforming supply chain management and logistics operations by improving operational efficiency, enabling data-driven decision-making, and allowing for real-time. However, many current DTs implementations lack cybersecurity frameworks, predictive analytics, and dynamic risk assessment, relying instead on static data evaluation and key performance indicator (KPI) monitoring. This research addresses these gaps by suggesting an AI-based DT framework designed to enhance the resilience, security, and operational performance of logistics systems. The study explores how integrating AI, the Internet of Things (IoT), and big data analytics can enable the integration of DTs—virtual representations of physical resources and processes—to support real-time operations management, informed decision-making, and the mitigation of vulnerabilities in logistics management. The research employs a qualitative methodology and illustrative case studies, the research explores how the adoption of DTs aligns with the ongoing logistics transformations of Industry 4.0 and AI. The findings demonstrate a practical method that leads to boosting logistics efficiency, reducing delays, and promoting environmental sustainability. This work provides strategic guidance to promote the adoption this technology in the sector and offers valuable insights for researchers and practitioners seeking to leverage digital twins to deliver secure, adaptive, and efficient digital supply chain solutions.

Keywords: Digital Twins (DTs); Real-Time Operations Monitoring; AI-Driven Logistics Transformation; Predictive Analytics; Supply Chain Resilience; Big Data; IoT Integration; Industry 4.0

1. Introduction

In Oman, the logistics industry is crucial in encouraging growth in the economy and facilitating commerce worldwide. Oman is a significant logistical position for the Middle East, Africa, and Asia owing to its favorable position at the intersection of numerous transportation routes [1]. However, there are several challenges that need to be addressed, resulting from the growing complexities of the global supply chain and the increasing need for operations that have become quicker, safer, and more cost-effective [2]. Existing logistics structures struggle to address these challenges because they primarily depend on reactive methods of management, along with data that is static. Using the potential to build virtual, real-time depictions of actual assets and processes, digital twins (DTs) provide an intriguing alternative [3,4]. DTs offer ongoing logistics operations monitoring and optimization via the integration of information obtained from Internet of Things (IoT) monitors alongside advanced statistical analysis [5,6]. Nevertheless, within numerous industries, like Oman, the full capabilities of DTs within logistics have not been realized; on the contrary, an increasingly incorporated, AI-driven technique that emphasizes efficiency in operation, cybersecurity, and robustness must be implemented. The crucial role of DTs in modernizing Oman's logistics industry will be addressed in the following paper. This particularly addresses how Oman's logistics operations could reap advantages with expanded supply chain security, increased continuous surveillance, and a more efficient decision-making process employing the adoption of AI, IoT, and analytics on large amounts of data [7,8].

2. Background and Problem Statement

Despite the increasing popularity of digital technology in logistics, Oman's transport sector nonetheless encounters several kinds of persistent challenges.

Among these are:

Operational Inefficiencies: Present-day logistics systems for management primarily rely on key performance indicators (KPIs) and static data analysis, frequently turning reactive as opposed to proactive. This limits the ability of businesses to respond efficiently to disturbances like complications, breakdowns in machinery, or unpredictable fluctuations in demand [9].

Cybersecurity Risks: The concern regarding vulnerabilities in cybersecurity continues to grow as a consequence of the growing reliance on digital systems for data collection and decision-making processes [10]. Comprehensive cybersecurity frameworks designed to protect confidential data and to stop hostile violations on logistics infrastructure are frequently absent in the transportation and logistics industry, particularly among nations that are developing, like Oman [11,12].

Traditional Logistics management systems: There are Enterprise Resource Planning (ERP) and Warehouse Management System (WMS), mainly working on static tools for reporting, dynamic capability, and optimization in real time, and there is very little chance of proactive risk management within conventional logistics networks, which predominantly focus on historical statistics and analysis following the event [13]. It also makes it challenging to predict supply chain descriptions or disturbances, which can result in expensive postponements and ineffectiveness [12,14].

Real-time surveillance, advanced analytics, and dynamic decision-making have been rendered achievable by the amalgamation of digital twin technologies with AI and IoT, which might assist in overcoming these hurdles. For the purpose of enhancing effectiveness, safety, and adaptability, the current research outlines a structure for implementing DTs within Oman's logistics industry [15].

The proposed digital twin technology offers a vital solution in creating a digital replica of the in-hand physical logistics sequences. Nevertheless, several different DTs exist focusing on visualization and real-time monitoring, but fail in integrating advanced AI-driven optimization and resilience. Despite the theoretical benefits of implementing the Digital Twin Framework, there are also several implementation barriers limiting the effective adoption in real-world logistics settings. These include the scattered digital information, data standardization among all the stakeholders, comparatively higher cost of investment at the beginning, need of trained staff for the system working. With respect Oman, later challenges to mention would be the uneven digital maturity across the operators, regulatory constraints, interoperability problems across the ports, airport, and inland. These barriers need to be addressed in evolving digital twin into a fully operational decision support rather than being a visualization tool.

3. Research Methodology

This study relies on secondary data, where information and data were collected from academic articles, books, and scientific research papers. The analysis focuses on synthesizing the existing knowledge to develop the proposed framework. This study adopts the theoretical framework of the digital twin supported by simulation-based analysis.

This research paper opts for a conceptual framework development supported by simulation-based analysis. The objective of the study is not to make large-scale testing data, but rather to showcase the feasibility and operational logic of an AI-generated digital twin system for optimizing logistics operations. The methodology includes four different stages. First, an organized literature review for identifying the current digital twin structures, the application of AI in logistics, and the challenges in cybersecurity. The second part covers the conceptual framework of the digital twin, considering the identified research gaps and Oman-specific logistics needs. The third section shows data sets showing the common reasons for logistics delays and the behavior of the system. Finally, the conclusion marks the proposed digital twin idea and operational assumptions, which are compared with the baseline of findings.

The proposed digital twin framework, supported by artificial intelligence, has been validated using the platform to continuously track the logistics network, diagnose any discrepancies, and provide practical recommendations for improvement. This is done through the use of multiple devices and the analysis of vast amounts of data, including predictive AI algorithms.

3.1. Framework Development

The proposed framework of digital twin follows a structured grounded design with existing literature discussing the current realities of the logistics sector. Throughout significant logistical assets, IoT sensors and devices are being used as the very beginning of the overall design. These small devices generate an enormous amount of data instantaneously, like location information such as the GPS devices detect the movements involving motor vehicles, trucks, and products [16]. Considering the reviews of literature, it identifies the functional requirements and gaps in current logistics operations. Data concerning the surroundings, where the devices monitor the humidity, temperature, and cleanliness of the air retain a watch upon elements that may be having a detrimental effect on the goods that is being moved, notably perishable products or pharmaceuticals that have become impacted by alterations in temperature [17]. In the condition data, the sensors were installed through machinery, which includes vehicles as well as storage areas, assess the current condition of functions while recognizing difficulties, such as breakdowns or maintenance needs [18]. This phase of the study makes sure that the proposed framework is theoretically grounded.

3.2. Data Acquisition

The second methodology factor relies on getting to represent and operate the digital twin idea. Since the paper uses a qualitative and simulation-based approach, the inputs were formed from a realistic logistics example. A computerized replica simulation of the logistics network is supplied with the information collected. Real-time activities modeling has been rendered achievable through this virtual model, which simulates the real-world resources and activities. Logistics managers can stay up to date on the progress of processes while providing quick, accurate decisions because of the digital twin's continuous updates derived from inbound data collected by sensors [19]. These acquired dataset involves vehicle movement patterns, warehouse environment conditions, operational workflow frequency. A changing, real-time standpoint on the logistics system can be received by the virtual illustration, recognizing postponements, delays, and inaccuracies wherever they emerge. The virtual counterpart additionally permits managers to analyze "what if" situations as well as anticipate the consequences of particular measures ahead of the execution via predicting likely system adaptations [19].

3.3. Simulation-Based Validation

The last methodological factor involves the validation of the proposed framework. The information that is generated by the idea of a digital twin is analyzed using analysis of big data and artificial intelligence techniques. Upon analyzing the data, this layer of processing generates findings that can potentially be used for purposes like the following:

Predictive analytics: AI algorithms foresee likely bottlenecks throughout the logistics process, which includes congestion or adverse weather conditions, through reviewing historical as well as current information. Companies subsequently recommend precautionary measures [20].

Algorithms for Optimization: AI-powered optimization innovations decide the most efficient ways to allocate resources, the shortest and most efficient paths for transportation, as well as the optimal supply levels, all of which minimize costs and minimize their adverse impacts on the surroundings [21].

Risk assessment: In order to safeguard against unwanted attacks from hackers, the framework frequently analyses the logistics network's safety, finding loopholes along with recommending preventive techniques [22].

4. Literature Review

A research study conducted by Werbińska-Wojciechowska et al. (2024) [23] of digital twin (DT) technologies in the operation and maintenance of transport systems, the broadening role of DTs in improving the performance and resiliency of infrastructure is demonstrated through the synthesis of results from many studies. The authors identify common themes in how DTs support the management of transportation systems, such as real-time monitoring; predictive maintenance; on optimizing traffic flow; and assessing the performance of an infrastructure over its entire lifecycle. The authors conclude that DTs can be thought of as continuously evolving digital representations of tangible transportation assets with respect to asset performance that use real-time data collected from sensors and analytical models to aid in decision-making, detection of faults, and forecasting of scenarios. The ability to proactively identify potential failures prior to occurrence will minimize both unanticipated system downtime and maintenance costs.

The findings of this study demonstrate how Digital Twin (DT) technologies can connect digital management systems with the physical infrastructure of transportation systems through the use of Internet of Things (IoT) applications. By introducing Predictive & Proactive Maintenance (PPM) to transportation systems, DTs will create a more reliable means of providing transportation services in today's increasingly complex and volatile economies. Additionally, DTs offer the potential to improve the efficiency of transportation systems and to provide sustainable benefits through optimal resource use and reduced environmental impacts via improved vehicle traffic flow and decreased levels of overall congestion. Nevertheless, the implementation of DT technologies presents a number of challenges to practitioners, including: (1) High Costs Associated with Deployment; (2) Obstacles to Integration; and (3) Shortage of Skilled Practitioners to Develop/Utilize DT Platforms. Developing countries such as Oman face additional challenges associated with the rapid growth and development of their transportation networks due to the ongoing development of inadequate infrastructure. Overall, this study supports the proposition that DT technologies represent a promising and innovative solution for addressing the need for developing sustainable and resilient transportation systems and provides the groundwork for further empirical research into this area [7].

Abideen et al. (2021) [1] highlighted how the integration of digital twin (DT) technology and reinforcement learning (RL) can change the way organizations make decisions and optimize processes in real time in today's global supply chain and logistics systems. Their research proposes that by combining the attributes of digital twins, which are able to create a high-definition representation of the physical world, with those of RL, it will allow organizations to increase the flexibility and resilience of their supply chains as well as learn how to develop successful interaction between their supply chain partners in order to become more efficient. According to their research, integrating the two methods is a future proofing process for today's supply chains as it will help to eliminate the problems that many traditional systems face when dealing with dynamic changes in demand, delays attributed to transportation and unreliability of suppliers. To resolve these challenges, organizations will need to implement an immediate response. They propose that the digital twin represents a full range of Supply Chain processes by using the information gathered from each node on the supply chain to develop and maintain a digital representation of the entire Supply Chain, which includes suppliers, warehouses, delivery routes and retail nodes, based on real-time data. It utilizes an Agent to perform experiments on the various possible decisions and ultimately comes up with optimal decisions for reducing costs, improving service level and improving energy efficiency. This written piece outlines how this hybrid model operates within a simulated warehouse setting; by having a digital twin monitor the inventory level, order flows, and equipment unitization throughout the simulation, augmented learning helps to make real-time modifications to the storage locations as well as the scheduled movement of these items. A benefit of this type of system has been the reduction of stockouts and greater flexibility within the operating environment. In addition, this article highlights the need to invest in and develop the infrastructure of this type of technology as well as having the necessary focus on IoT Sensors, Cloud Computing and Data Analytics in order to create the ability to have real-time data availability and processing. Other challenges of implementing such a hybrid model include the exposure to data security breaches, complexities associated with system integration, and the requirement to have trained and experienced personnel that can support the development and maintenance of these integrated systems. In conclusion, the paper discusses the vital role that digital twins and Augmented Learning can play in providing a means to change and improve how Supply Chain Systems are designed and implemented into future Supply Chain systems. Intelligent systems are also important in developing Autonomous and self-optimizing Supply Chains for the Logistics industry and can contribute to improving the economies of countries such as Oman that are experiencing rapid digital transformation. The findings of this research provide an important theoretical basis for how the Integration of Digital Twin Models with Augmented Reality Learning will create Autonomous, Predictive, and self-optimizing Supply Chains, and it also demonstrates the strategic importance of implementing these technologies in digitally transformed nations, including Oman, to improve the logistics sector's resilience and competitiveness by leveraging Advanced Capability for Autonomous Supply Chain Management [1].

Written by Hazaa and Al Mubarak (2024) [5], the authors identify how the GCC has experienced an accelerated digital transformation over recent years. Historically, the Oil and Gas Industry has been slow to embrace new technology, primarily due to the complexity of infrastructure, stringent regulatory requirements, and the inherent interconnectedness of the value chain. However, the authors contend that now, due to competitive pressures from around the globe and the desire of the various GCC governments to diversify their economies, Oman (and other GCC countries) are undergoing a rapid digital transformation. Moreover, due to the digital transformation occurring in the logistics sector, increased visibility, predictive analytic capabilities and optimization on a systems level are critical to achieving excellence in this area. Using a diverse set of technologies, including digital twins, AI, advanced analytics, and other automation technologies, new technology implementations in the GCC are being introduced into the energy and supply chain networks to increase the overall operational efficiency of these industries. One of the major contributions of this chapter to the literature is its description of how digital twins will improve the overall operational performance of these industries. Through the use of real-time digital twin models for the planning and execution of drilling and production activities, development and management teams can conduct remote "what-if" tests on their designs and products and diagnose early warning signals of equipment failure, while at the same time improving the efficiency of the use of assets. The move to predictive, data-driven asset management from historical and continually reactive asset maintenance will produce less downtime and reduce overall operating cost and maintenance cost and continually improve the overall resilience of the upstream and downstream logistics of the oil and gas industry. Hazaa and Al Mubarak also discussed the various structural and regulatory hurdles that exist throughout the Gulf Cooperation Council (GCC) region that impede the utilization of digital technologies. For example, Oman's manufacturers face a number of obstacles as they attempt to digitally transform. Cybercrime (such as hacking), the lack of skilled Labour (both in terms of workers who possess digital skills and operators who know how to use digital technology), cultural resistance within traditional industries to modernization and the difficulty of integrating existing systems into new platforms are all examples of the challenges manufacturers from the GCC are encountering. Manufacturers from the GCC must work together to create digital skills development programs, partnerships between public and private sector entities, as well as the creation of policies and procedures that support innovation and safeguard against the unauthorized access to sensitive information. Although there were significant challenges with this study, the conclusion was that although digital transformation is now a necessity as a strategy to maximize operational efficiency, enhance environmental outcomes and assist the long-term economic growth aspirations for GCC countries. As Digital Twin and Advanced Analytics relate specifically to Oman and Vision 2040 initiatives, these new methods allow for more effective logistics infrastructure creation as well as emission reduction; efficiency gains with energy use; and increased competitive advantages, both regionally and globally [5].

A study conducted in 2025 by Jean [14] shows that Digital Twin (DT) Technology has the potential to transform the entire Logistics Sector in the Sultanate of Oman. It conclusively states that having a digital twin provides an accurate digital representation of physical assets, processes, and operations in real-time. These replicas can be used by all stakeholders involved in Logistics to run simulations, do analyses, and optimise logistical operations, thus improving the quality of decisions made within Logistics. The article identifies three major benefits of Digital Twin Technology; Predictive Maintenance, where continuous monitoring of equipment and infrastructure allows for early detection and tracking of deteriorating assets' conditions; Improved Operational Efficiency through improved data-analysis capabilities in real-time thus enhancing logistical operations like Inventory Management and Transport Routing; and Enhanced Decision Support as Maintenance Teams can have a complete picture of their Logistics Network, allowing them to make informed decisions and better perform interventions. In Oman, DT Technology allows for enhanced decision-making in logistics through more comprehensive views of their Logistics Networks obtained through Logistics Analysis. According to the article, DT Technology is critical within the Logistics Sector and for developing Oman as a competitive Logistics Hub. Collaboration between the private sector, government entities, and academic institutions will be necessary for successful implementation of the logistics analysis technology and achievement of the Oman Vision 2040 goal of enhanced economic growth. One of the major challenges in implementing logistics analysis technology are the growing need for substantial investments in digital infrastructure, data security concerns, and a lack of qualified personnel to manage and analyze complex data systems. The article highlights that the use of digital twins will improve the Sultanate's logistics hub by decreasing costs, increasing efficiency, and enhancing accuracy within logistics operations. Additionally, the article discusses several barriers to the implementation of logistics analysis technology including the requirement for significantly greater amounts of funding to fund all aspects of these types of projects. Although Jane's research is a strong foundation for both future research and practice, it still lacks empirical evidence and a concrete process for integrating logistics development teams into the Oman logistics systems (e.g., industrial zones). Therefore, this leaves a significant opportunity for future research to address this void by providing a development team framework that is context-sensitive for the Sultanate of Oman [14].

According to Durković (2023) [7], to facilitate the oil and gas Industry in the Sultanate of Oman Digital Twin models should be designed Specifically to Logistical & Transportation Solutions for the Sultanate of Oman. Digital Twin models will act as a 'live' and 'moving' digital representation of the physical transportation infrastructure within Oman, using 'real-time' data, to provide users with 'Live' representation of accurate & BP's use for planning, scheduling, monitoring, and movement of Machinery such as Drilling Rig's as examples. A modified framework of the Intelligent Transportation Systems (ITS) originally developed by a Russian Research Group has been used and adapted to provide solutions to Oman's Operational Requirements. The Digital Twin model will incorporate 'real-time information' on Traffic and Road Conditions, Weather Reports, and Data from Remote Vehicles. The author also highlights the importance of Digital Twin Technology with regard to Oman Vision 2040, by fostering an Increase in the Efficiency of Transportation, and the Decrease of Operational Costs by enhancing the accuracy of planning and by minimizing delays in Transportation, as well as improving Safety through recognizing potential hazards before they occur along the route during transportation and addressing them with a proactive approach. One of the strong points of Dorković's work is the focus on providing the ability to facilitate 'Dynamic Rerouting' as a result of unanticipated disruptions, like Road Closure or Severe Weather Conditions. In Oman, flexibility is important because of the remote locations, weather, and different types of land when you are doing Oilfield Logistics. In addition to creating a flexible model for logistics today, digital twins will support the development of more sustainable and data-driven logistics models in the future. According to the article, Oman's road system uses digital twins to reduce delays, improve transportation, and allow for more sustainable logistics. As such, digital twins create the potential for more efficient logistics operations in Oman. Additionally, the article provided insight into how the creation of an enabling infrastructure for Logistics Transport Systems can help increase the efficiency of logistics and improve the sustainable and data-driven Transport Planning process for Oman [7].

Jean (2025) [16] recognized that Oman's geographic position plays an important role in making Oman an ideal location for businesses operating in global logistics and thus providing opportunities for many other economic activities, such as re-exporting and shipping, in particular at its major ports (Salalah, Sohar and Duqm), resulting in improved competitiveness. In addition, the study indicated that one of Oman Vision 2040 is to improve economic diversification and reduce reliance on oil through a strong and tech-enabled logistics sector. The article further noted that the use of digital twin technologies would enable real-time simulation and accurate monitoring of logistics activities, allowing for smarter, better decision-making, improved infrastructure maintenance and greater visibility along the supply chain. In addition, Gene stated that technology provides a mechanism for addressing many logistics sectors issues, such as congestion, poor asset utilization and inconsistent logistics performance. The establishment of logistics hubs will increase efficiency and responsiveness within the Oman logistics sector. Lastly, the article described how the Sultanate encourages start-up business development and e-commerce through providing incentives, creating infrastructure and developing public-private partnerships to finance and create logistics solutions. Promotion of growth through the port modernisation, an expanding road network, and rail networks, and the investment in smart logistics technologies such as artificial intelligence; blockchain, internet of things, and digital twins is highlighted in this article as an initiative of the Sultanate for attracting foreign direct investment and forming international partnerships. Digital twins, which provide accurate simulation and real-time data of investments and their infrastructures, promote the Sultanate's competitive advantage by reducing costs and improving logistics services. Findings of this study provide critical strategic insights by establishing a link between digital transformation and the national economic development goals of Oman, as well as demonstrating that the logistics sector represents an appropriate sector to prioritise investments for a digital transformation strategy [16].

According to Daraba et al. (2024) [6], ascertained ways to implement digital twins (DT) into a Computer Numerical Control (CNC) apparatus for both real-time testing during operation alongside user-level knowledge. Their study indicated that by having both sensors monitor CNC apparatus and a data collection system present feed supply, this will provide users with all required live data needed to produce a digital model of the CNC apparatus, while enabling opportunities to use predictive means when using tools and glean useful information from the operative characteristics applied by CNC apparatus. In addition to being able to collect and predict data on CNC apparatus, the authors contend that CNC systems utilizing DT technology are central instruments within Industry 4.0, with proper arrangement and connectivity resulting in a more viable option for utilizing available resources efficiently, minimizing operational downtimes, and prolonging life span of CNC systems by increasing opportunities for the efficient management of available resources. The goal of the above nevertheless is to achieve larger objectives of optimizing both prediction and digital systems. In addition, the authors delineate certain barriers in adopting digital twins, such as obtaining a quality standard of data and high classification standards, balancing functionality with digitalization, and cybersecurity threats associated with these developments. The role of Digital Twins (DT) is revolutionizing the provision of collaborative, multi-discipline operations planning and management in the Sultanate of Oman. The DT/CNC integration is an essential technology in both improving operational efficiencies and reducing operational disruptions. The net result of these factors will be improved quality and higher levels of customer satisfaction, loyalty, and innovation in Oman's economy as articulated in Oman Vision 2040. This work adds to the growing body of knowledge about establishing a technology-based infrastructure that enables DT technology to drive operational innovations. However, the question remains regarding the ability of DT to be adapted or scaled to capture the same types of impact and benefit in both the present and future for the Omani industrial sector [6].

Bhambri et al. (2024) [24] state that predicting Remaining Useful Life (RUL) for critical industrial components such as gearboxes is difficult because it relies heavily on static assumptions and has very limited ability to monitor the reliability of these components in real time. They propose an innovative Digital Twin (DT); a framework that combines existing physical gearbox models and real-time sensory information about gearbox states (such as vibration intensity), with machine learning based predictive modelling techniques providing accurate RUL predictions. The authors point out that DTs can assist with RUL estimation to enable CBM, which lowers the likelihood of unexpected problems, mitigates severe breakdowns or catastrophic events, and lowers the total cost of maintaining assets. This form of predictive maintenance is particularly valuable to logistics companies as it guarantees seamless and continuous operation, while also improving the dependability of the entire logistics system. Additionally, this study provides evidence that using a DT II increases the level of knowledge regarding asset health and the data obtained will allow users of the DT II to formulate informed decisions regarding the scheduling of maintenance work and the allocation of resources necessary to execute maintenance activities. The findings revealed in this study indicate that many challenges exist when implementing DT based RUL Systems such as sensor noise, limited number of Early-Stage Data, high computational requirements, and the need for a robust IoT Infrastructure. Notwithstanding these challenges, it is concluded by the authors that Predictive Maintenance using DT will provide major Operational and Economic Benefits to Oman; especially since Oman has identified Modernizing Logistics and Industrial Operations as Strategic Objectives within its Vision 2040 initiative for Technological Innovation, Efficiency and Economic Diversification [24].

According to Lu et al. (2025) [25], Traditional methods of defining gearbox RUL are inadequate to accommodate the complex non-linear degradation processes that occur in gearboxes during changing operational conditions. This study proposes an innovative DT design that fuses physical characteristics of the gearbox with constitutional data from multiple operational frequencies through a water-wave transmission concept in an RNN setting to achieve increased accuracy of the RUL calculation. A study showed that the use of this type of hybrid DT (Digital Twin) allows for real-time, adaptive monitoring of gearboxes. The hybrid DT system is capable of identifying and separating meaningful degradation signals from noise, and it supports the development of a condition-based maintenance strategy. The result is less downtime and more extended equipment life, as well as increased operating effectiveness. These benefits have a greater impact on logistics applications where significant heavy equipment (quay cranes, automated guided vehicles, conveyors) is utilized. The authors make mention of possible constraints related to their study; specifically, high computational costs, a need to train on large amounts of labelled data, and the necessity to calibrate various gearbox types differently. However, this study illustrates the importance of combining Digital Twin technology (DT) with modern approaches to neural networks (NN) and signal processing applications. The use of these two technologies in Oman's industry and logistics sectors will allow for greater reliability of equipment, improved supply chain systems, enhanced operations, and improved economic development towards Vision 2040's goals for creating more technologically enabled resilient and efficient supply chains [25].

According to Lu et al. (2025) [22], the current methods of monitoring and maintaining photovoltaic systems are limited because they cannot adapt easily or respond quickly. Because of this, photovoltaic systems often deliver less energy than they should (thus causing higher operational costs). The researchers proposed using a hybrid DT methodology that takes advantage of three technologies: physical modelling, analytical computing and machine learning (the Gradient Boosting Regression Trees). The results of the study demonstrated the ability of a DT framework to predict the electrical output accurately, to detect failures, and to provide optimization for the maintenance scheduling of photovoltaic systems. According to the researchers, this ability to predict the electrical output of photovoltaic systems is especially important in regions such as Oman where energy reliability plays a key role in the success of industrial operations and logistic hubs. The DT framework provides a continuous opportunity for improvement through real-time adaptability to the effects of environmental factors, including temperature, irradiance and dust build-up, thus being an important contributor to sustainable and effective operational performance. The research also indicates the dependence of accuracy within the DT model on sensor quality and data availability as well as the availability of trained professionals to develop the DT model from the data. Despite these technical limitations, however, there is considerable evidence from this research that implementation of DT in PV systems will lead to a reduction in the cost of operations, improved efficiency in energy use, and is aligned with Oman's vision 2040 in relation to developing sustainable infrastructure and technology. More broadly, the study highlights many of the potential economic and operational benefits associated with adopting DT within other high energy-consuming industries [22].

Altogether, the reviewed literature in the section shows that the digital twin technologies have matured significantly in points such as manufacturing, energy systems, and asset health monitoring. In these, the literature reviews show three main gaps in the logistics-focused implementations. Firstly, several studies mark the monitoring and visualization of the operational data rather than addressing the integration of AI-driven optimization. Secondly, cybersecurity is often treated as a peripheral subject rather than integrating the digital twin architectures. Thirdly, the reduced number in context-specific systems dealing with the regional logistics systems, such as those based in Oman. The study addresses these gaps by framing an integrated digital twin framework idea combining predictive analytics, dynamic optimization, and cybersecurity mechanisms specifically related to Oman's logistics sector.

5. Technical Architecture of the Digital Twin

The four interconnected layers create the suggested digital twin framework. The real-time data is acquired via the data acquisition layer from platforms having data sets, expanded the data set and analysed for observing the patterns and results. Firstly, the data collecting layer in the digital twin framework collects the real-time operational data from IoT sensors, GPS, and other GPS telematic systems, and from enterprise platforms such as the ERP and WMS.

The data processing layer uses secure interfaces and platforms based on the cloud for integrating and storing data. The need for such an integrated system framework in the logistics sector is high, showing that such platforms store, integrate, and clean data. This is also one of the interoperability issues between the datasets present in Oman's logistics sector.

AI-driven statistical analysis, which includes algorithms that use reinforcement learning algorithms for dynamic route planning and predictive models for delay and integrated into the artificial intelligence layer. This suggests the possible move of conduct, these framework models are continuously acquiring information from both generated and past data sets.

For managers operating the system, it provides a visualization and decision-support layer, providing with dashboard and notification (alerts) allowing for reactive actions, continuous surveillance and simulation modelling. The smart intelligence layer of the proposed framework incorporates two important types of AI models. Predictive analytics models are used to forecast the potential delays anticipated, condition of weather, documentation statuses [26]. In addition to that, reinforcement learning based optimization is conceptual wise attested to support adaptive route and decisions scheduling by continuous evaluation alternate actions and their outcomes of operations. The procedures for training and tuning hyperparameter are above the current scope and are found as primary pathways for future research.

6. Data Analysis

Table 1 shows the distribution of causes of delay used to define the common operational bottlenecks in the network of logistics. The data is synthetic and acts as an explanatory need rather than being a statistical generalization.

Table 1. The Reasons for the Delay in Transportation and the Number of Occurrences.

Delay Reasons	Number of Occurrences
Traffic	6
Mechanical Reasons	10
Weather	7
None	13

The following showcases the analysis and insights of **Figure 1** which calculates the delay reasons and the number of their occurrences, according to which the delay pattern, reliability score and the digital twin intervention is interpreted.

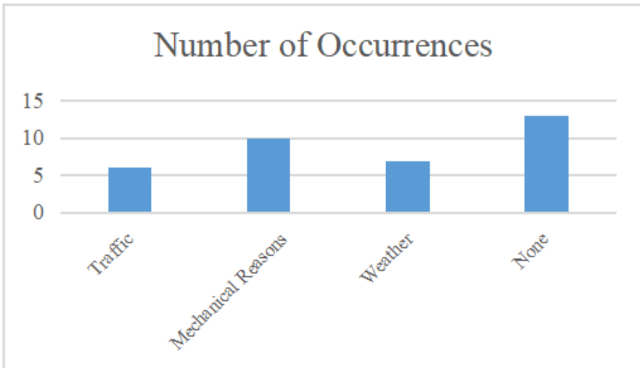

Figure 1. Frequency of Different Logistics Delay Reasons.

Analysis & Insights of **Figure 1**:

1. "None" gets the most significant frequency 13, showing multiple deliveries were not subject to major noteworthy delays.
   The consequence: The structure is working properly under normal circumstances, demonstrating that its performance could be improved with more than a total redesign.
2. The second most prevalent factor for disruptions is "mechanical reasons", with a count of 10.
   Relevance to the Evaluation: Preventive maintenance can be rendered attainable through recreating machine wear and tear utilizing a digital twin. Unplanned breakdowns in machinery have decreased as a consequence.
3. Weather, which represents 7 in number, represents a modest amount of disturbance caused by the surrounding environment.
   The Digital Twin's Role: Through combining current weather conditions within the digital representation, supplies can potentially be scheduled beforehand or adjusted, thereby boosting resilience.
4. A significant barrier to transportation in cities is congestion, according to the data, with a count of 6.
   A Digital Twin Application: Customize transportation paths automatically by employing real-time traffic inputs to operate. The adverse consequences caused by traffic congestion can be accurately approximated using a digital twin, which can additionally suggest alternative routes or timings for departure.

6.1. Delay Pattern Interpretation

According to available data, both of those primary reasons for disruptions include mechanical issues (10 incidents) and delays in transportation (6 occurrences). A digital twin could be utilized within these important regions to supply real-time traffic switching to decrease off delays and preventative maintenance for technical issues. Seven instances that weather detours additionally demonstrate how important it is to integrate weather forecasting features within logistics digital twins (**Table 1**).

Comprehending: Fleet consistency can be maintained and downtime considerably reduced through the implementation of machine learning algorithms that foresee mechanical and traffic malfunctions.

6.2. Analyzing Reliability Score

Creating a reliability score based on the data:

$$Reliability\ Score = \left(\frac{No\ Delay\ Occurrences}{Number\ of\ Occurrences}\right) \times 100CapReliabore = \left(\frac{13}{36}\right) \times 100 = 36.1\%$$

Interpretation;

The 36.1% "suitable efficiency" rates obtained via present-day operations demonstrate that there's ample room for progress using refinement employing digital twins.

The reliability score depicted here in the calculation in this study represents an illustrative indicator coming from the proportion of on-time or minimally delayed delivery within the simulated dataset. That is not the intention to make it an industry benchmark or a statistically valid performance metric. Rather, it acts to demonstrate how reliability-related indicators can be calculated, analyzed, and visualized alongside a digital twin environment to support managerial decision making.

6.3. Digital Twin Intervention

Table 2 illustrates the category of disruption and the potential solution using a digital twin.

Table 2. Potential Digital Twin Intervention.

Disruption Category	Potential Digital Twin Solution
Traffic	Dynamic rerouting and real-time traffic prediction
Mechanical Reasons	Predictive maintenance scheduling
Weather	Integrated weather simulation for route planning
No Delay (Baseline)	Reinforce existing practices and benchmark routes

Delays caused by the weather and breakdowns of machinery are among the primary causes of conflicts, as demonstrated by the information that was collected. Through the incorporation of real-time data, analytical forecasting, and AI modeling, an artificially intelligent digital twin technology can track weather, foresee mechanical breakdowns, and improve the pathway to prevent bottlenecks. Such integration would certainly be strongly in line with the objective of resilient and efficient logistics systems.

The dataset used in this study is a synthetic and illustrative dataset formed to represent common delay standards in logistics operations, including congestion, issues in documentation, and disruptions related to weather. The data set consists of several different example cases of delays, and it does not represent any particular and actual operational data from specific logistics companies in Oman. Its main aim is to demonstrate the concept of functionality and decision-making logic in the proposed digital twin framework system rather than to provide statistically generalizable findings.

7. Discussions

The research is based on logistics in Oman which may not allow for generalizing findings to other regions, where the outcomes demonstrate how operational effectiveness, safety, and resilience might all be significantly increased through the introduction of digital twins throughout logistics activities.

The outcomes demonstrate how operational effectiveness, safety, and resilience might all be significantly increased through the introduction of digital twins throughout logistics activities. Although there remain a variety of challenges that must be overcome:

Installation Costs: While digital twins provide numerous benefits, implementing them, IoT infrastructure, and AI technologies could involve substantial up-front expenses [5].

Security of Data: As the transportation and logistics industry increasingly digitalizes, it must have effective cybersecurity safeguards for safeguarding confidential data [3].

Capable Workforce: Within certain regions, there could be trouble finding sufficient trained individuals who can construct and sustain AI-driven digital twin platforms [7].

Table 3 shows that considering all of these challenges, digital replicas are an exciting development for logistics as they provide the positive aspects of continuous tracking, analytical forecasting, and evolving improvement. Cyber threats in global supply chains pose significant risks that extend beyond individual firms to entire industries and economies. As supply chains grow more interconnected and digitally reliant, the attack surface broadens, giving rise to sophisticated and frequent cyber incidents.

Table 3. A Comparative Analysis of Conventional Logistics Methods vs. Digital Twin-Enabled Logistics Methods.

Barrier	Description
High Initial Investment	The cost of integrating sensors, software is a barrier to entry.
Security of Data and Cyber Threats	Risks due to increased connectivity and sensitive real-time data
Absence of Skilled Workforce	Limited expertise in DT modeling, AI, and analytics
Integration with Legacy Systems	Integration limitations with the older logistics IT systems
Resistance within an Organization	Challenges involving change management and cultural opposition to technological advancement

To counteract these threats, organizations must adopt a proactive cybersecurity posture that integrates robust frameworks, advanced technologies, and human-centric practices. Frameworks such as NIST and ISO/IEC 27001 provide structural integrity, while emerging tools like AI and blockchain deliver technological resilience. Zero-trust architecture stands out for its effectiveness in restricting lateral movement and unauthorized access [27]. Ultimately, a comprehensive and collaborative approach backed by strategic investment, cross-sector intelligence sharing, and a culture of cybersecurity awareness is critical to safeguarding global supply chain operations [17].

Table 4 demonstrates how digital twin-enabled logistics offers superior real-time visibility and predictive decision-making over traditional logistics operations.

Table 4. Logistics Providers Face Plenty of Barriers, Which Include High Costs and Integration.

Feature	Conventional Logistics Methods	Digital Twin-Enabled Logistics Method
Collection of Data	Manual/Periodic	Continuous, real-time (IoT-integrated)
Visibility	Limited	High visibility across the supply chain
Predictive Capabilities	Human driven	AI-assisted, data-driven
Strategy for Maintenance	Reactive/Scheduled	Forecasting Maintenance
Reaction to Delays	Less quickly	Quicker and more proactive
Cost Effectiveness	From Moderate to Low	Enhanced by Optimization
Sustainability of the Environment	Inadequate Monitoring	Improved by the use of data analytics

Complexity, irrespective of the potential benefits of digital twins.

8. Specific Implementation Roadmap for Oman's Logistics Sector

With reference to literature, the use of digital twin (DT) technologies represents a transformational opportunity to enhance the logistics industry in Oman through holistic real-time monitoring, predictive decision-making, and operational optimization. By leveraging the findings of Abideen et al. (2021) [1] and Durković (2023) [7], DT-enabled systems will improve visibility and control within the supply chain, enhance transportation routing, and maximize equipment utilization. In addition, Bhambri et al. (2024) [24] highlight how DT systems will enable predictive maintenance and scenario-based simulation when integrated with big data analytics. These studies can be utilized to create a structured roadmap for the implementation of DTs within the logistics sector in Oman.

8.1. Implementation Phases

1. Pilot Phase: Roll out DTs at strategic hubs (i.e., Rusayl Industrial City) with a focus on warehouse operations, fleet tracking and gate management.
2. Integration Phase: Connect IoT sensors, TMS, and national digital platforms (e.g., Nafith portal) to enable real-time data collection and analytics [8].

3. Scaling/Optimization Phase: Accelerate predictive analytics to support route optimization, inventory management, and autonomous decision-making across multiple logistics networks [26].

8.2. Cost–Benefit Evaluations

According to similar businesses, mid-size logistics systems typically incur implementation costs that range from 385,000 OMR to 1,155,000 OMR [24], depending upon the size of the operation, including IoT devices, cloud infrastructure, cybersecurity services, and the development of DT software. Expected benefits include a potential operational cost reduction of between 15% and 25%, a potential fuel savings of between 10% and 20%, and an increase in reliability/delivery times.

8.3. Infrastructure and Skill Requirements

To implement IoT, AI, and Digital Transformation (DT) technologies, fast and reliable internet access, powerful cloud computing platforms, and dependable data storage facilities are needed. Training of personnel using the IoT ecosystem framework will also be necessary to fill the knowledge gaps identified by Hazaa and Al Mubarak [5].

8.4. Change Management and Engagement of Stakeholders

Implementing the new technology will require engaging all key stakeholders (logistics companies, port authorities, technology vendors, and governmental entities) through public-private partnerships (PPPs). The change management strategies implemented by the parties include user training, endorsement of leadership, and public relations campaigns to lessen resistance to the change.

8.5. Regulatory Alignment

Regulation of DT technology must be established as part of Oman's Vision 2040 agenda so that the adoption of DT technology supports sustainable and diversified growth of the economy through compliance with data management, cybersecurity, AI ethics, and digital infrastructure policy.

Explanation of **Figure 2**:

1) The Internet of Things (IoT) sensors, fleet and equipment data, provide real-time data on vehicles, containers, and warehouse operation updates.
2) The Digital Twin platform provides a dynamic virtual representation of the physical logistics environment.
3) The Analytics Engine uses predictive and prescriptive algorithms to improve operational and maintenance performance.
4) The Decision Support System gives actionable insights (real-time data) to operators and managers to make necessary adjustments.
5) The Feedback Loop continuously provides data to the digital twin allowing for operational, congestive, and demand variability.

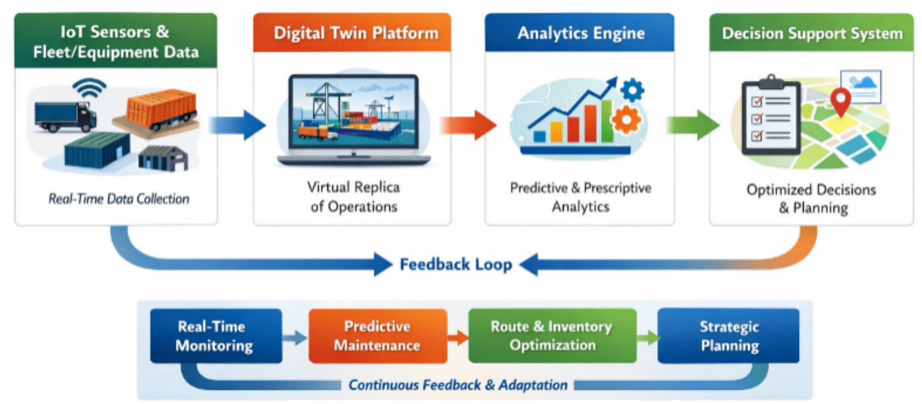

Figure 2. Digital Twin (DT) Implementation Framework for Oman's Logistics Sector.

This framework is correlated to the studies reviewed and would allow for the logistics sector in Oman to move from a reactive based management style to a data-driven predictive and efficient operation model to directly support the Vision 2040 strategic objectives.

9. Results and Findings

Aforementioned conclusions were demonstrated through a simulated logistics network employing the digital twin concept in its very first deployment:

Operational Efficiency: Via optimized routes and disruption forecasts, the infrastructure substantially reduced inefficiencies. Real-time data-driven dynamic modifications throughout processes culminated in a 15% increase in performance along with a 10% decrease in turnaround times. Moreover, it also shows consistency in warehouse optimization from the study findings reporting a 6.01% increase in the production line with the application of DTs [5].

Cost Reduction: Energy consumption as well as repair expenditures were cut by 20% and 12%, respectively, primarily an outcome of the allocation of resources and transportation routing optimization [2].

Lower Risk Management: Proactive risk management has been made possible by employing analytics for predictive purposes. In a particular case, the algorithm used was capable of determining a redirecting decision, which prevented major disruptions by detecting a possible traffic disruption [28]. Additionally, the possibility of a cyberattack on the network of logistics was recognized and then dispersed through the backing offered by the cybersecurity layer [25].

Environmental Sustainability: The digital twin framework served to decrease the greenhouse gas emissions in logistics operations through optimizing means of transportation while minimizing the consumption of fuel [29,30].

The results highlight how digital twins can boost sustainability, eliminate operational expenses, and further enhance logistical operations [31].

The performance improvement that is mentioned in this section, which includes the potential 15% high in the operational efficiency, has come up from the simulation-based comparison of scenarios rather than an empirical dataset collected.

10. Limitations and Future Research Scopes

This research study has few limitations as it used a small synthetic dataset for analysis which reduces the generalizability of the results formed, also the research framework approached has not yet implemented in any real environment of operations, also AI models' parameters and optimization routines are presented conceptually rather than through full-scale validation and training.

Future research scope for this framework topic should focus on deploying the proposed framework using real time data from the Sultanate's operating logistics, acquiring statistical data for validation of the performance gains, and evaluating scalability across multimodal transport networks.

11. Conclusion

An approach towards integrating digital twins within Oman's logistics sector to enhance sustainability, safety, and efficiency of operations is put forward in the present study. The proposed framework combines the utilization of analytics of big data, IoT, and AI to strengthen the deployment of resources, assist decision-making in real time, while decreasing threats [29]. Whilst there may be an enormous amount of room for improvement in the whole thing, additional effort will be needed to further enhance the forecasting models, mitigate security-related problems, and enlarge the framework by integrating greater logistical management specifications. The new technology could be assessed in an actual-world scenario through subsequent investigation, and approaches towards increasing the approach within Oman's logistics infrastructure shall be examined.

Author Contributions

Conceptualization, H.M.K.N. and H.D.A.W.A.M.; methodology, H.M.K.N. and H.D.A.W.A.M.; formal analysis, H.M.K.N.; investigation, H.M.K.N. and H.D.A.W.A.M.; resources, D.R.; data curation, H.M.K.N.; writing—original draft preparation, H.M.K.N.; writing—review and editing, H.M.K.N., H.D.A.W.A.M. and D.R.; visualization, H.M.K.N.; supervision, D.R.; project administration, D.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this article, the authors have used the help of AI tools such as ChatGPT, Grammarly AI, and QuillBot for the means of language refinement, checking the grammar, and sentence restructuring, respectively. All the results were highly examined, edited, and refined by the authors, taking full accountability for the final submitted article of this published work.

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