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Leveraging Digital Twin Technology to Improve Logistics Operations Efficiency in Saudi Food Manufacturing

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Abstract
The complexity and uncertainty of logistics operations require organizations to improve data integration, process visibility, and decision-making. This study examines the effect of Digital Twin Technology on Logistics Operations Efficiency in food manufacturing companies in the Kingdom of Saudi Arabia. A quantitative cross-sectional design was adopted, and data were collected through an electronic questionnaire from 195 employees and managers working in food manufacturing companies in Saudi Arabia. Digital Twin Technology was examined through five dimensions: Real-Time Data Integration, Bidirectional Connectivity, Virtual Representation and Simulation Capability, Data Analytics and Predictive Capability, and Operational Services and Decision-Support Capability. Logistics Operations Efficiency was assessed in terms of resource and time utilization, reduced waiting and downtime, minimized delays and unproductive movements, and improved material flows. Data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The findings indicate that all five dimensions have positive and statistically significant effects on Logistics Operations Efficiency. Data Analytics and Predictive Capability showed the strongest effect ($\beta = 0.27$, $p < 0.001$), followed by Real-Time Data Integration ($\beta = 0.24$, $p < 0.001$). The overall Digital Twin Technology construct demonstrated a positive effect on Logistics Operations Efficiency ($\beta = 0.72$, $p < 0.001$), explaining 52% of its variance. The study provides empirical evidence supporting Digital Twin adoption to improve logistics efficiency in Saudi food manufacturing.

Keywords: Digital Twin Technology; Logistics Operations Efficiency; Real-Time Data Integration; Saudi Arabia.

1.Introduction

The world of manufacturing is changing very quickly and the Fourth Industrial Revolution has extended information technology, industrialization and automation beyond automation and into truly smart production and logistics environments with increased integration, connectivity and responsiveness. This shift has made companies more vertically and horizontally integrated in their production and logistics networks, as well as the technologies developed starting from the Internet of Things (IoT), Cyber-physical systems, Advanced analytics, Artificial Intelligence and Digital Twin technology that have reduced the physical and virtual gap. The technologies are especially relevant for logistics operations, as they today are exposed to growing complexity and uncertainty, multiple sources of risk, and a high demand for fast reaction to changes in the logistics operations. Hence, to accelerate the logistics performance, the capability of organizations in obtaining accurate and timely information to evaluate alternative operations and to make rapid Anschauung is essential (You & Feng, 2020; Noveloia & Prieto, 2017; Kaiblinger & Woschank, 2022).

In this context, Digital Twin (DT) technology emerges as one of the key technologies able to change the way the management of industrial and logistics systems is carried out. A Digital Twin is an evolving dynamic digital replica of a physical system or entity that is always linked to the physical through a data exchange; it includes being able to observe its state and performance and predict its behavior in a virtual space. Today, the significance of this technology is not limited to the creation of a virtual copy of a real-world system: more importantly it enables embedding data, models, simulation and analytics to enable monitoring, prediction, decision making and continuous improvement. Digital Twins have now moved beyond their initial use in Lifecycle Management (LCM) to find uses in production, planning, maintenance, process design and logistics. The literature suggests that the foundations of Digital Twins moving beyond simple representation and monitoring and the ability to support analysis, optimization and operational decision making is through integration with the physical entity and the ability for bidirectional communication and real time data updating (Glaessgen & Stargel, 2012; Batty, 2018; Kritzinger et al., 2018; Tao et al., 2019; Kaiblinger & Woschank, 2022). These capabilities are especially important in logistics, where maximizing flow and minimizing delays and costs relies on traffic coordination and both managing the various types of inventories and managing the timetable for all these activities, plus responding to shifting of demand, resource availability, and operating conditions. The Digital Twin can give a current perspective on the operational situation, create alternative scenarios of operation to test before an actual implementation, anticipate problem scenarios in advance, make better use of resources and improve flow coordination, and make faster decisions. Yet the move from the theoretical to measurable, industrial use of Digital Twins, is still difficult. From the literature, it can be noted that there are still a few challenges with Digital Twin applications related to data integration, interoperability between different systems, real-time synchronicity, and the lack of a uniform application framework, suitable for an industrial environment integration (Kritzinger et al., 2018; Kaiblinger & Woschank, 2022; Sharma et al., 2022; Zhu et al., 2023; Tao et al., 2024).

This problem is significant for the food manufacturing industry due to characteristic features of enterprise operations that make it particularly sensitive to the efficiency of warehouse and logistics operations. Frequently, food products have limited shelf life, are susceptible to the passage of the day and temperature and have strict quality and safety requirements. Precise coordination of the production, storage, transport and distribution activities is more important than ever in these conditions. A result, interrupted processes, lack of information or poor resource management can lead to a loss in revenue, waste food, allow food products to spoil and compromise delivery. Digital Twins, in turn, provide a chance to optimize food operations by visualizing real operation processes, simulating operating scenarios, optimizing schedules and material flows, as well as make decisions based on data. These capabilities have been introduced in recent studies, with the aim of using Digital Twin technology in the food sector to achieve tangible ambient performance benefits, but there is still a lack of empirical evidence on this subject in the area of food (Iacovanelli et al., 2024; Croci et al., 2025).

The main importance of this issue in Saudi Arabia stems from the investment that is increasingly being directed towards the food industry to improve food security, diversifying the national economy, and enhancing the production capacity. Saudi Vision 2030 and National Industrial Development and Logistics Program (NIDLP) have elevated food manufacturing to a part of the initiatives for boosting local industrial production and enhancing the supply chains and logistic services essential to supporting industrial production. They are backed by the creation of food industrial specializations, the promotion of their links with agricultural production and logistics services and the improvement of the competitiveness of local food products. Therefore, logistics efficiency is key to a more competitive industrial base, bolstering food security, enhancing logistics capabilities and accelerating the use of cutting-edge digital technologies that form part of Saudi's vision to establish a more efficient economy (National Industrial Development and Logistics Program 2021).

Although the value of Digital Twin for improving logistics efficiency is being highlighted in the literature more and more, the knowledge available is still incomplete to fully grasp the value of Digital Twin in logistics. Numerous studies have centered on the concept and definition of DTs, their architecture, their degree of maturity, and their use cases, but statistical evidence to directly demonstrate the impact that DT capabilities have on the logistics operations' efficiency has been limited. While simulation, case studies and technology-oriented applications have been the main areas of research in food manufacturing, firms and logistics professionals have not occurred as much in quantitative studies of this relationship. This gap, especially in Saudi Arabia, is crucial. Indeed, as the Kingdom is bolstering its food manufacturing capacity and further strengthening its industrial and logistic framework, the need for empirical evidence has emerged to validate the potential of Digital Twin technology to deliver real gains in terms of the efficiency of food manufacturing logistics is undeniable (Kaiblinger & Woschank, 2022; Sharma et al., 2022; Zhu et al., 2023).

For this purpose, the current study investigates the impact of Digital Twin technology on logistics operation efficiency of Saudi food manufacturing companies through a quantitative modelling approach which reflects the elements of Digital Twin technology and evaluates their influence on the logistics operations efficiency. The operational significance of Digital Twins in an under-researched Saudi context adds to the body of empirical evidence as it avoids merely presenting Digital Twins as a new technological opportunity and explores the operational potential of these twins. The findings are expected to provide practical insights for food manufacturing companies seeking to leverage Digital Twin technology to improve logistics efficiency while supporting Saudi Arabia's broader transition toward more digitally enabled and technologically advanced industrial operations.

2. Literature Review

2.1 Digital Twin Technology

Digital twin (DT) technology has evolved as a workhorse technology that provides useful connection between the physical and digital world, and offers monitoring, analysis and optimisation of systems. As operational systems become more complex, uncertain and demands for quick data-driven decisions, this technology has become more important in manufacturing and logistics (Haße et al., 2019; Kaiblinger et al., 2021; Resman et al., 2021; Woschank et al., 2021). The digital twin concept dates back to Grieves' model in product life cycle management that connected the virtual and physical worlds by sharing data and information (Grieves, 2014). It has since expanded to wider industrial uses such as in planning, production, maintenance, process improvement or optimization and logistics (Kritzinger et al., 2018; Tao et al., 2018; Tao et al., 2019).

Though digital twins have become widespread, there is no universally accepted definition of digital twins from the existing literature, with the range of use in different areas and the different digital twin characteristics that researchers can focus upon (Kritzinger et al., 2018; Stark & Damerau, 2019; Tao et al., 2019). In general, a digital twin is a digital model of a physical object or system that an observer can see, describe or measure (International Organization for Standardization [ISO], 2020). This representation can be applied to a product, process, service or organizational system (Qi et al., 2019). A digital twin, however, is not the same as a conventional digital model as there is a continuous and dynamic relationship between the physical system and its digital twin. The virtual model represents the status and behavior of a physical system and facilitates inter-challenge interactions between the two systems (Parrot & Warshaw, 2017; Tao & Zhang, 2017).

Digital twins are valuable because of their essential features, such as real-time data integration, and because they are two-way communication tools. Data transfer from physical system to virtual model allows for the virtual model to be continually updated, and data analysis and information from the virtual environment inform decisions or interventions in the physical environment (Tao & Zhang, 2017). This integration helps keep the two systems in sync and to maintain continuous process monitoring (Kuehn, 2018). In addition to representing the current state of the system, the digital twin can serve to simulate, predict, analyze different scenarios, optimize, and make decisions (Glaessgen & Stargel, 2012; Qi et al., 2019; Tao et al., 2018).

Several conceptions of the architecture of the digital twin have been presented in the literature. According to Grieves there were three key elements, the physical domain, virtual domain, and the means that connected the two – data, information and processes (Grieves, 2005). Although subsequent works have elaborated more complete digital twins' conceptions to include the physical object alongside virtual object, the other virtual components being data, services, and communication technologies, this is reflective of the "integration" nature of the digital twin technology (Tao et al., 2018; Qi et al., 2019). This implies that the digital twin is not confined to a virtual system but rather on data, communication, the analytical and operational services they provide and the ability to interact with the physical system normally, continuously.

The digital twin can be utilized in a variety of production and logistics functions, such as the planning and control of production, logistics operations, warehouse management, resource allocation, planning, monitoring and optimization, among others (Kritzinger et al., 2018; Tao et al., 2018; Tao et al., 2019). It can also be integrated with Enterprise Information system, enabling data and information flows for operating monitoring and decision support (Kuehn, 2018). The literature shows that the impact or validity of a digital twin depends significantly on the depth of integration of the components of the digital twin, on the continuous updating of data, and on the capacity to correlate digital information with real information from real decision and real processes. Though many relevant applications in logistics have been conceptual, experimental, or at an early stage of implementation, deployments have also shown the potential of the technology in various aspects like routing, scheduling, resource allocation or forecasting and decision support (Kritzinger et al., 2018; Vachálek et al., 2021).

According to this study, the digital twin technology can be understood as a dynamic digital system which comprised data integration and communication, digital simulation, digital analytics, digital operation and services, linking physical system and processes to a synchronized virtual system and processes. This allows for the process to be monitored, forecasted, analyzed in alternate ways and for decision support with the aim of process improvement (Glaessgen & Stargel, 2012; Qi et al., 2019; Tao et al., 2017; Tao et al., 2018). The knowledge is the base on which the dimensions of digital twin technology will be built and measured in the current study.

2.2 Logistics Operations Efficiency

A key component of efficient performance in industrial facilities is logistics efficiency. It is associated with the efficiency and effectiveness with which the material handling and transportation function can be performed, without unnecessary queueing losses of time and material. With the aim of cost-cutting and enhancing productivity, companies are being urged to evaluate the efficiency of their logistics operations within the company. The need to measure and review the efficiency of internal logistics operations has increased with the goal of reducing logistic costs and increasing productivity being of great importance to industrial companies. This is particularly the case as production efficiency not only relies on manufacturing process, but also on the efficiency of logistics related activities in the flow of materials inside the manufacturing units (Oechsner et al., 2002; Huang et al., 2002; Huang et al., 2003).

Production logistics involves a series of activities associated with the transport and handling of materials that occur during any production sequence or in production at the production site to ensure the flow of material between work steps or work places in the factory. In this view, logistics efficiency relates to the system's performance in terms of making these happen in a productive way within the available time frame. For this reason, not only the evaluation of final production results, but also losses in the implementation of internal logistics processes should be taken into account (Coşkun & Erturgut, 2022).

A practical approach for estimating production logistics efficiency of an organization in terms of time was developed by Seebacher et al. (2015). The concept is to look for time losses as they are in the execution of the logistical activities being done, and to compare them with the total time available to execute the activities. The view of logistical efficiency is seen as the fraction of time during which it is possible to perform the logistical activities by what is actually done. Therefore, the more time produced the less time lost, the more efficient the logistics. (Seebacher et al., 2015).

The sources of time lost affecting the efficiency of internal logistics operations are the main ones. Idle and downtime can be planned e.g., when someone needs time to rest or not sufficient demand for transport is placed or internal transport is not available e.g., when a bus fails or the resources are unavailable, or when someone prefers not to use public transport. The second is speed losses, where transport operations are slower than intended, as a result of low speeds of execution. The third inefficiency is the time that internal transport vehicles are in motion but are not actually transferring anything—this is known as empty runes. The losses accumulate over time and impact productive time, and hence on logistics effectiveness (Seebacher et al., 2015).

Thus, logistics efficiency can be defined as the capability of logistics system to transform the time and material that is available to engaging in productive logistics activities with a minimum loss of time and unproductive speed, and avoidance of delays and waiting. From this perspective, the relevant literature on measuring production system efficiency highlights the work of identifying operational losses and measuring the effect of these losses on productive time, for example how much time and effort are wasted on using the equipment or with the support for production (Jonsson & Lesshammar, 1999; Oechsner et al., 2002).

Measuring logistics efficiency is not an attempt to measure it now, but an attempt to find out the inefficient areas in logistics and steer improvement efforts to overcome them. The method proposed by Seebacher et al. (2015) was used to identify the losses in time in the internal logistics processes, thereby determining the inefficiencies in the considered internal value chain and evaluating the corrective action taken and comparing the efficiency before and after the implementation of the solution. This method enables the turning of an efficiency measurement process from a standstill to a process which can facilitate the ongoing enhancement of logistics processes.

With the possibility of information systems and identification and tracking technologies to automatically collect information of the manufacturing process in real time, modern manufacturing environments are bringing this concept into focus. The knowledge of transport times, stops, waiting times, speed and empty trips allows analysis when it comes to detecting improved efficiency and loss in the actual transport process more accurately and timely (Coşkun & Erturgut, 2022). This means logistics operation efficiency is becoming more and more dependent on the ability to keep monitoring processes constantly, keep accurate operational data, analyze losses and take actions based on information to improve.

Based on this, the current study uses the Logistics Operations Efficiency concept which is the ability of logistics operations to utilize available time and resources efficiently, with minimal downtime, waiting time, speed losses, and inefficient movements or trips. This idea can be well developed and applied in the study of the application of digital twin technology, as this technology has the ability to monitor in real time, integrate data, analyze processes and simulate alternatives, which can help to decrease the sources of loss and help to use logistics resources more productively.

2.3 Theoretical Foundation

The current study is based on a resource-based view (RBV) to explain how digital technologies can contribute to creating operational value within companies. This perspective emphasizes that resource ownership alone does not necessarily translate into value, but rather how effectively they are used and can contribute to resource learning and enrichment in achieving better outcomes in the processes. According to literature, information technology (IT) plays an important role to facilitate the acquisition, processing, and flow of information among the different entities in the supply chain, thus assisting decision making, communication, and coordination, and collaboration among the various supply chain's stakeholders (Grover & Malhotra, 1999; Wu et al., 2006).

This perspective also highlights that value that can be generated with technology is not an automatic outcome of employing it, but rather depends on how it is used and on the integration within the supply chain processes. Wu et al. (2006) suggested that the value of IT capabilities is dependent on how well an organization can use them to change processes in its supply chain and its relationships with its stakeholders. Likewise, Fawcett et al. (2011) also convey that IT capabilities could be used to create higher level capabilities and their results show that these capabilities have positive influence on customer satisfaction and operational performance.

The digital twin is treated as a representation of IT's new capabilities as it is founded on data and analytics to bring operational value. The data and analytics-driven value creation is significantly similar to the digital twin-driven value creation, as per the data and analytics work as enabling components for creating value driven by digital twins according to Qi and Tao (2018). Thus, the digital twin could be seen as a technology that would be incorporated into the process of the supply chain, rather than as a technology, which is outside of the process of working in the organization.

This is consistent with the theory of dynamic capabilities as the capacity of the organization to integrate, build, and reconfigure its internal and external capabilities to respond to rapid and uncertainty changes (Teece et al., 1997). It was this perspective that Chen et al. (2015) adopted to describe the use of the big data analytics in supply chains. They found big data analytics to be a dynamic capability--it enabled the processing of information, uncertainty reduction, creation of knowledge, and capacity improvement for strategic decisions for organizations. From this perspective the Digital Twin may be seen as a Digital capability based on data and Analytic, which is continuously used to enhance process understanding and improvement.

Moreover, the value that digital technologies provide can occur at a number of levels, ranging from business process to the capabilities in the supply chain and finally to enterprise-wide performance. A clear example of this is that Meriton et al. (2020) showed how value in supply chains is multilevel concept and how big data analytics can be applied to the improvement of several processes of the supply chain, including demand management, order fulfillment, product management, production management, supply chain management and customer service. This can then be manifested as improved capacities like agility, resilience, collaboration and organizational performance. The logic here is that there's potential to move some of the value generated at the digital twin level to the process level and then to the answers to operational outcomes.

Therefore, in this study, Rapid Range Value (RBV) is used as a basis for interpreting digital twin technology's relationship with logistics efficiency. Digital twins, however, don't magically deliver efficiency when they are part of a company, but when they are a part of a company that can use them operationally and think about how to do things more efficiently and more effectively based on their leveraged input. Hence, the study investigates whether digital twin technology can be operationalized as actual value in logistics in the food sector of Saudi companies. The concept of making the value of technology depends on its use and integration into an organization's processes and how it is used to improve the performance of the organization rather than just investments in technology.

2.4 Digital Twin Technology and Logistics Operations Efficiency

The longer the processes in the logistics system are elaborate and the more interactions between the various resources and activities, the more efficient execution of these processes becomes. This reduces the ability of traditional operational decision-making procedures to deal with the changing operating demands and operating conditions. In such cases, the digital environment can be created via digital twin technology by artificial reproduction of the logistics system in reality, where operational data can be entered into the simulation and analysis model. That enables the learning about the manner of operation of the system and the testing of operation options prior to their deployment in the real-world environment (Jia & Jiang, 2017 & Agalianos et. al., 2020).

Determination of applied evidence suggests that digital twins have potential to directly enhance the logistics landscape in terms of their application as a monitoring, analysis and decision-making tool. Ashrafian and Pedersen (2023) created a digital twin, modelling intermittent phenomena in a large-scale automated order picking and processing system in a fresh food warehouse. The digital model near-real-time integrated with the WM/OPS, using a vast amount of real operational data from the warehouse. The study revealed the usefulness of digital twins to analyze the performance of the system, test different scenarios, and support the decision-making process needed to increase the operational performance of a complex logistics system.

Moreover, Leng et al. (2021) describe the ability of digital twins to go beyond monitoring to optimizing (or redesigning) logistics processes. They created a digital twin system consisting of a physical warehouse system with data collection and a cybers system to connect the data. This system then includes a model of optimization of the packing processes and storage location allocation in a combined way. This architecture enables regular creation of better decisions, and then testing in a simulation environment. The case study demonstrated that Digital Twin application can be used to improve the use of resources and warehouse system efficiency, strengthening the link between using a Digital Twin and improving operational performance in logistics operations.

This is discussed with Kauke et al. (2021), who discussed the use of digital twins in order picking systems to aid the operational control. They show that digital twins coupled to simulation can serve as the basis for studying the processes and operational decisions made when using an order picking environment, and also be used to evaluate different scenarios prior to implementation. Essentially, it shows that the power of digital twins in logistics comes with the capacity to convert operational data into actionable insights that can be employed to both influence and optimize resource and process decisions.

In very dynamic and complex systems this relationship is very relevant, as the results of operational decisions cannot be reliably estimated with traditional techniques. With digital twins, a digital copy of the real system can be created, operational information can be added to this digital copy, and different scenarios can be tested by allocating a certain number of resources, detecting bottlenecks, predicting operating time, defining order capture policies, or simulating material flow. Prep work like this can be helpful in identifying inefficiencies, assessing alternative operational options, and in choosing the most effective options prior to the actual implementation in the system (Agalianos et al., 2020: Kauke et al., 2021: Ashrafian and Pedersen, 2023).

These practical examples help to substantiate the hypothesis that a digital twin does not only enable a virtual model of the logistics system, but also allow for a connection to operational data and integration for monitoring, analysis, simulation, decision support and optimization. Digital twins, which can better capture and continuously improve the actual situation of a system, can be leveraged more efficiently to uncover system bottlenecks, shorten wait times, improve resource utilization, and better manage process flows. Therefore, based on the applied literature, it can be assumed that there will be a positive relationship between the level of use of digital twin technology and the efficiency of logistics operations.

Based on this, this study will hypothesize that the use of digital twin capabilities in food manufacturing enterprises can help increase logistics efficiency, both through the use of dynamic process representation, real-time operational data, simulation of options and decision-making support in material and resource flow, scheduling, storage and distribution. Especially in the food industry, logistics operations must be coordinated, fast, and precise because the nature and time sensitivity of products. In the light of this, this study extends from the evidence of the potential of digital twins to enhance the performance of the specific logistics systems and evaluates it in food manufacturing companies in Saudi Arabia.

2.5 Hypothesis Development

2.5.1 Real-Time Data Integration and Logistics Operations Efficiency

One of the operational values of DT is in real-time data integration. In order for a digital twin to be effective, it requires continuous information from various operational sources, and real-time syncing with the virtual system to capture changes in the physical system. Integrating sensor, operational and historical information with digital models and analytical tools is emphasized in Qi et al. (2019), and the on-going information exchange needed to guarantee the convergence between the physical and virtual worlds is brought forward in Tao and Zhang (2017).

This capability is particularly important for logistics operations, where efficiency depends on timely information regarding inventory, orders, resources, material locations, and transportation activities. Kaiblinger and Woschank (2022) indicate that integrating operational data with digital representations can enhance visibility, monitoring, planning, and decision-making in production logistics. In food supply chains, Huang et al. (2026) further demonstrate that Digital Twin adoption can improve information visibility and coordination across production, inventory, distribution, and order fulfillment, with improvements in inventory levels, delays, and unfulfilled orders. Similarly, Maheshwari et al. (2023b) found that integrating Digital Twins with procurement, production, and distribution supported real-time planning and control and improved scheduling, lead time, capacity utilization, and service levels. Therefore, real-time data integration can improve logistics operations efficiency by enhancing operational visibility, reducing information gaps, accelerating the detection of deviations, and improving coordination among materials, resources, and orders. Accordingly, a positive relationship is expected between real-time data integration and logistics operations efficiency.

H1: Real-time data integration has a statistically significant positive effect on logistics operations efficiency in food manufacturing companies in Saudi Arabia.

2.5.2 Bidirectional Connectivity and Logistics Operations Efficiency

Both Communication from the Physical to the Virtual and Bidirectional Connectivity, allowing information to flow from the physical to the virtual dimensions and vice versa, are essential to make a Digital Twin operational. Tao and Zhang (2017) highlight the importance of connectivity and interaction in ensuring the convergence of the aforementioned domains, while Qi et al. (2019) too name connectivity as one of the key aspects that enables the physical entity, virtual model, data, and digital services. Bidirectional connectivity, from the operations and supply chain point of view, allows outputs from the analysis to be translated to operational decisions and actions. This is in line with the concept of the Resource Based View, which posits that the added value of technological resources comes about through application of them in organizational processes (Wu et al., 2006). Leng et al. (2021) implemented a Digital Twin in logistics by linking real-time warehouse data in real-time and taking advantage of simulations for testing warehouse decisions without making them. Likewise, Agalianos et al. (2021) demonstrated how Digital Twins based simulation can be combined with operational data to enhance continuous monitoring, scenario evaluation and operational decision making. Thus, bidirectional connectivity can establish a continuous loop which connects data, analysis, decision making and execution, enhancing people's responsiveness, people and resource synchronization, and the flow of materials. Hence, increasing in the bidirectional connection is desired to improve logistics operations efficiency.

H2: Bidirectional connectivity has a significant positive effect on logistics operations efficiency in food manufacturing companies in Saudi Arabia.

2.5.3 Virtual Representation and Simulation Capability and Logistics Operations Efficiency

Digital Twin technology can be transformed from monitoring into Virtual Representation and/or Simulation Capability to evaluate the system behavior and operational alternatives. Kritzinger et al. (2018) define the development of the Digital Twin as an extension and intensification of the physical system into the virtual world, and Tao et al. (2019) attribute that the creation of the virtual model is an essential part that will facilitate the monitoring, analysis, and optimization of the physical system when combined with data and analytical services. The ability to simulate changes to the schedule, resource deployment, transportation, and storage function in this sort of logistics system can be very useful to help organizations test effects without actually causing disruption to the physical processes. In a Digital Twins simulation, digital twins and simulation can be used to demonstrate a system analysis, alternative evaluation, planning and decision-making, as noted by Kaiblinger and Woschank (2022). Likewise, Leng et al. (2021) found that a Digital Twin, combined with warehouse data, could help to optimize packing and warehouse placement decisions using a simulator to validate decisions. For food manufacturing, Maheshwari et al. (2023a) found that Digital Twin implementation helped improve resource allocation, utilization, effectiveness and throughput. Hence, "virtual" and "simulation" can assist in recognizing bottlenecks, exploring alternatives, optimizing resources usage, and minimizing waiting times and improve logistics operation efficiency.

H3: Virtual representation and simulation capability has a significant positive effect on logistics operations efficiency in food manufacturing companies in Saudi Arabia.

2.5.4 Data Analytics and Predictive Capability and Logistics Operations Efficiency

Data Analytics and Predictive Capability allows the Digital Twins to convert operational data into information and knowledge, helping to understand the situation at hand and predict events. Digital Twins, as outlined by Qi et al (2019), are the combination of the sensor, operational and historical data with the analytical models to enable diagnosis, prediction and optimization. In a similar way, Chen et al. (2015) define Big Data Analytics as a capability to process information which generates knowledge, decreases uncertainty, and enhances decision making. Therefore, data value is related to being analyzed and applied to the operational processes. In the field of food logistics, this is especially relevant due to the varying demands, altering stocks, production plans for food and its distribution, and time-invariant factors involved in food products. By leveraging their capabilities for real-time monitoring, predictive analytics, and supply chain visibility, Digital Twins have the potential to enhance inventory management, order fulfillment, and minimize delays, as shown by Huang et al. (2026). Maheshwari et al. (2023b) also observed that the Digital Twin's integration with procurement, production, and distribution facilitates integrated planning, more accurate estimation of reorder point, better scheduling, lead time, and productivity. Thus, predictive analytics can provide an organization with a way to foresee shifts in demand, predict possible bottlenecks, gauge the necessary resources, and prevent delays from happening at all. It can significantly minimize the losses of time, and optimize the use of resources and make logistics more efficient by changing the mindset of decision-making from reactive to proactive.

H4: Data analytics and predictive capability has a significant positive effect on logistics operations efficiency in food manufacturing companies in Saudi Arabia.

2.5.5 Operational Services and Decision-Support Capability and Logistics Operations Efficiency

Operational Services and Decision-Support Capability is the point at which digital Twin data, models, analytics and simulation output is turned into information that is used to help plan, schedule, allocate resources, manage inventory and coordinate material flow in a new way. The services are recognized as a crucial element of the Digital Twin architecture by Qi et al. (2019) and they enable the monitoring, diagnosis, prediction, and optimization functions. Tao and Zhang (2017) also point out that the fusion of the physical and virtual world allows for interaction, control and intelligent operation management. This relationship resonates with the concept of the Resource-Based View that proposes that technological resources generate value through the by-products of the process of embedding the resources in the organization and converting them to capabilities that yield performance enhancements (Wu et al., 2006). In the logistics field, Kauke et al. (2021) and Leng et al. (2021) showed how Digital Twins can be applied as a tool for order picking/packing/warehouse allocation to operational control and the evaluation of alternatives. Ashrafian and Petersen (2023) also demonstrate that a DT can be integrated to real operational data in an automated food warehouse to contribute to a support for monitoring the performance, scenario analysis and decision making in the food warehouse automation. Likewise, Maheshwari et al. (2023b) highlighted that by leveraging Digital Twin integration throughout procurement, production, and distribution, a greater emphasis can be placed on improving various key areas such as planning, scheduling, lead time, capacity utilization, and service levels. Therefore, outputs from Digital Twin can be turned into effective operational decisions through operational services and decision-support capabilities. These functions can minimize delays and waste in operations and optimize logistics efficiency by optimizing sequentially, resources, inventory, and material flow.

H5: Operational services and decision-support capability has a significant positive effect on logistics operations efficiency in food manufacturing companies in Saudi Arabia.

2.5.6 Digital Twin Technology and Logistics Operations Efficiency

Besides analyzing the five dimensions separately, the overall Digital Twin Technology–Logistics Operations Efficiency relationship is studied, in which the Digital Twin Technology is defined as an integrated technological capability, comprising bidirectional connectivity, real-time data integration, virtual representation and simulation, data analytics/prediction, and operational services and decision support. According to Qi et al. (2019) and Tao et al. (2019), the utility of Digital Twins comes from the combination of physical and virtual entities, providing monitoring, analyzing, and optimizing services as well as data and connectivity. Technological value, as perceived from the RBV, relies on the technological value in terms of involvement with organizational processes, as well as transforming it into capabilities that enhance organizational performance (Wu et al., 2006). This relationship can be empirically validated. Digital Twin applications in food manufacturing and supply chain operations enhance optimal use of resources, throughput, planning, scheduling, lead time, productivity, and service levels as reported by Maheshwari et al. (2023a, 2023b). In the same way, Leng et al., 2021 have shown the possibility for the optimization and simulation of data to be utilized in the real-time allocation of storage expenses and packing choice, in addition to optimizing resources. Other applications of Digital Twins in production logistics, identified by Kaiblinger and Woschank (2022), include monitoring, planning, simulation, optimization, and decision support. In the field of logistics, Ashrafian and Pedersen (2023) show how Digital Twins can be used for performance monitoring, scenario analysis, and enhancing the logistics system; Huang et al. (2026) have shown that food supply chain Digital Twin adoption improves inventory levels, delays, unfulfilled orders, costs, and food waste. Thus, Digital Twin Technology can be considered as the combination of complementary digital capabilities. Digital Twins can help of course to decrease delays, to use all possibilities of resources and material flows optimization, and finally to try to improve the efficiency of the logistics operation itself by integrating all of the above points; real time information, connectivity, simulation, predictive analytics and decision support.

H6: Digital Twin technology has a significant positive effect on logistics operations efficiency in food manufacturing companies in Saudi Arabia.

3. Methodology

3.1. Research Design

The current study employs a quantitative approach using descriptive analytical methodology because the study focuses on the facts and needed a method that can present the facts and make an analysis of the facts. These goals involve analyzing the dimensions of Digital Twin Technology and their relationship with Logistics Operations Efficiency. The study examines five dimensions of Digital Twin Technology, namely Real-Time Data Integration, Bidirectional Connectivity, Virtual Representation and Simulation Capability, Data Analytics and Predictive Capability, and Operational Services and Decision-Support Capability, and their effects on Logistics Operations Efficiency. The primary data gathered via a structured questionnaire to develop insights from the Saudi Arabian food manufacturing firms that have first-hand experience in supply chain processes, operations, logistics, warehousing, procurement, production, and digital transformation. Data obtained is then analyzed with statistical tools, in order to test the reliability and validity of the measurement instrument, examine the relationships between the study variables, and test the proposed hypotheses. The study also has a cross-sectional design which will be used to capture the perceptions of the respondents regarding the level of Digital Twin Technology and Logistics Operations Efficiency in the companies included in this study at a particular point in time.

3.2. Research Population and Sample

The study population comprises food manufacturing companies in the Kingdom of Saudi Arabia (KSA), a sector that is important and closely connected with food security, production processes, supply chain networks, distribution activities, and logistics services. This study targets employees in these companies who are directly involved in logistics, supply chain management, warehousing, production, procurement, information technology, digital transformation, and quality activities, and who have sufficient knowledge and experience to evaluate the study variables, namely Digital Twin Technology and Logistics Operations Efficiency.

The respondents were selected purposively in order to have relevant knowledge and hands on experience in the operational and technological activities studied. The final sample consisted of 195 respondents from food manufacturing companies in the Kingdom of Saudi Arabia. The demographic characteristics of the respondents, including gender, age, educational level, job position, work experience, functional area, company size, are presented in **Table 2**.

3.3. Data Collection and Research Instrument

The primary data was retrieved using a structured questionnaire aimed at gaining the perceptions of the employees in the food manufacturing industry in KSA about the Digital Twin Technology and Logistics Operations Efficiency. The dimensions and the measurement items were identified by reviewing the relevant literature and adapted to suit the food manufacturing and logistics operations, **Table 1**.

The questionnaire consisted of two main sections. The first section collected demographic information about the respondents, including gender, age, educational level, position, work experience, functional area, company size, and experience. The second section involved measurement of the study variables. The five dimensions of Digital Twin Technology consisted of five items each: Real-Time Data Integration, Bidirectional Connectivity, Virtual Representation and Simulation Capability, Data Analytics and Predictive Capability and Operational Services and Decision-Support Capability. Logistics Operations Efficiency was evaluated by the use of eight indicators that showed the capacity of logistics operations in using available time and resources as efficiently as possible and reducing delays, waiting time, and losses in the operations.

The respondents were asked to indicate their level of agreement with each statement using a 5-point Likert scale from (1 = Strongly Disagree to 5 = Strongly Agree). The questionnaire was completed by the employees who have the experience of working in operational, logistics and supply chain units or in relation to the various digital technologies, thus obtaining the answers after the right preparation regarding the study parameters.

A total of 195 valid responses were obtained and used for the subsequent statistical analysis. The collected data were coded and prepared for statistical analysis to assess the reliability and validity of the measurement instrument and to test the proposed relationships and hypotheses.

Table 1. Measurement Dimensions, Number of Items, and Main Sources

Variable / Dimension	*No. of Items*	*Main References*
Real-Time Data Integration	5	Qi et al. (2019); Tao & Zhang (2017); Kaiblinger & Woschank (2022)
Bidirectional Connectivity	5	Tao & Zhang (2017); Qi et al. (2019); Leng et al. (2021)
Virtual Representation & Simulation	5	Kritzinger et al. (2018); Tao et al. (2019); Kaiblinger & Woschank (2022)
Data Analytics & Predictive Capability	5	Qi et al. (2019); Chen et al. (2015); Huang et al. (2026)
Operational Services & Decision Support	5	Qi et al. (2019); Tao & Zhang (2017); Leng et al. (2021)
Logistics Operations Efficiency	8	Seebacher et al. (2015); Oechsner et al. (2002); Coşkun & Erturgut (2022)

3.4. Data Analysis

The electronic questionnaire technique was used to collect the data from the employees and managers of food manufacturing companies in the Kingdom of Saudi Arabia. 195 valid responses were received and analyzed. Respondents were provided with the information that the questionnaire was being conducted as a part of academic research, and participation was voluntary. Both confidentiality and anonymity of responses gathered have been respected during the research process.

Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to analyze the collected data. The analysis process was carried out in two main stages. The first one was the measurement model, which was used to check the indicators' reliability, internal consistency reliability, convergent validity, and discriminant validity. To assess internal consistency, the Cronbach Alpha, rho_A and Composite Reliability (CR) were calculated, and for reliability, factor loadings were assessed. The convergent and discriminant validities were assessed by the Average Variance Extracted (AVE) and the HTMT ratio and Fornell-Lacker criterion, respectively.

In addition, the structural model was evaluated, with the intention of testing the relationships between Digital Twin Technology and Logistics Operations that are hypothesized. The bootstrapping procedure with 5,000 subsamples was used for the estimation of path coefficients (β), their corresponding t-values and the associated p-values. The endogenous construct was evaluated in terms of its explanatory power (R^2), effect sizes (f^2) and predictive relevance (Q^2). The Standardized Root Mean Square Residual (SRMR) and Normed Fit Index (NFI) values were used to assess model fit. Last, hypothetical relationships of the five dimensions of Digital Twin Technology to Logistics Operations Efficiency as well as that of Digital Twin Technology to Logistics Operations Efficiency were investigated based on the significance of the path coefficients, their directions, and the conceptual consideration.

4. Results

4.1 Demographic Characteristics of the Respondents

A total of 195 valid responses were obtained from employees and managers working in food manufacturing companies in the Kingdom of Saudi Arabia. The respondents are identified from two segments: Logistics and Supply Chain Management, Warehousing, Production, Procurement, Information Technology, Digital Transformation and related operational functions. An overview of the composition and Prof. Background of the study sample was obtained by analyzing the demographic characteristics.

The respondents of the sample were mainly male (152--or 77.9%) and female (43--or 22.1%). As to age, the largest group of respondents were in the 33–44 age group (33.3%), followed by those aged 25–34 (24.6%) and 45–54 (24.6%). There were 4.8% of Respondents aged between 25 and 44, and 11.3% aged 55 years or over, and 6.2% under the age of 25.

In terms of their education, most of the respondents had a Bachelor's degree (64.1%) and then a Master's (23.1%). 7.2% of them had a Doctoral degree, 4.1% had a Diploma and 1.5% had other qualifications. Job position breakdown was dominated by Middle Managers (29.2%), Supervisors (23.1%) and Senior Managers (17.9%). The majority of sample employees were Operational Employees (16.4%) followed by Executive/Top Management (11.3%). Only 2.1% reported other job levels.

A distribution of respondents based on their work experience, those who had 11–15 years of experience, were the highest percentage (25.6%) followed by 5–10 years (24.1%) and 16–20 years (20.0%). 17.4% of the respondents had more than 20 years of experience and 12.8% of the respondents had less than five years of experience. The majority featured in the functional area distribution were in Production/Manufacturing (20.0%), Supply Chain Management (15.9%), Logistics (14.4%) and Information Technology/Digital Transformation (14.4%). Other functions related to warehousing, procurement, quality, and all other non-systematized processes accounted for approximately 12.3%, 11.3% and 8.2% and 3.6% respectively. Looking at the size of the organizations, 47.7% were large organizations, 36.9% were medium size and 15.4% were small organizations.

Table 2. Demographic Characteristics

Characteristic	**Category**	**n**	**%**
Gender	Male	152	77.9
	Female	43	22.1
Age	Under 25	12	6.2
	25–34	48	24.6
	35–44	65	33.3
	45–54	48	24.6
	55 or above	22	11.3
Educational Level	Diploma	8	4.1
	Bachelor's degree	125	64.1
	Master's degree	45	23.1

Characteristic	Category	n	%
	Doctoral degree	14	7.2
	Other	3	1.5
Position/Job Level	Operational Employee	32	16.4
	Supervisor	45	23.1
	Middle Manager	57	29.2
	Senior Manager	35	17.9
	Executive/Top Management	22	11.3
	Other	4	2.1
Work Experience	Less than 5 years	25	12.8
	5–10 years	47	24.1
	11–15 years	50	25.6
	16–20 years	39	20.0
	More than 20 years	34	17.4
Functional Area	Logistics	28	14.4
	Supply Chain Management	31	15.9
	Warehousing	24	12.3
	Production/Manufacturing	39	20.0
	Procurement	22	11.3
	IT/Digital Transformation	28	14.4
	Quality	16	8.2
	Other	7	3.6
Company Size	Small	30	15.4
	Medium	72	36.9
	Large	93	47.7
Total		**195**	**100.0**

4.2 Measurement Model Assessment

The measurement model was initially evaluated to establish the reliability and validity of the constructs before assessing the hypothesized structural relationships. The assessment included indicator reliability, internal consistency reliability, convergent validity, and discriminant validity. The measurement model comprised five dimensions of Digital Twin Technology, namely Real-Time Data Integration, Bidirectional Connectivity, Virtual Representation and Simulation Capability, Data Analytics and Predictive Capability, and Operational Services and Decision-Support Capability, together with Logistics Operations Efficiency as the endogenous construct.

As shown in **Table 3**, the standardized factor loadings ranged from 0.74 to 0.91. The majority of the indicators exceeded the recommended threshold of 0.70, demonstrating satisfactory indicator reliability. No indicator showed a loading sufficiently low to justify its removal, and all items were therefore retained because of their theoretical relevance and contribution to the content validity of their respective constructs.

The five-item Real-Time Data Integration construct demonstrated loadings ranging from 0.78 to 0.88. One to three items were loaded in the Bidirectional Connectivity dimension (range 0.76 to 0.87), and in the Virtual Representation and Simulation Capability up to 3 (range 0.75 to 0.89) items. The data analytics and predictive capability loaded from 0.79 to 0.90. For Operational Services and Decision-Support Capability, loadings ranged from 0.77 to 0.89.

The items pertaining to Logistics Operations Efficiency ranged in loading ranging from 0.74 to 0.91 for the 8 items measured. The overall findings suggest that the indicators are applicable for measuring the latent constructs and have acceptable samples of their respective constructs to support further examination for reliability and validity.

Table 3. Structure of the Instrument and Factor Loadings

Construct	Item	Statement	Loading
Real-Time Data Integration	RTDI1	Our company integrates operational data from different sources in real time.	0.84
	RTDI2	Operational data are continuously updated in the Digital Twin system.	0.88
	RTDI3	Our Digital Twin provides timely data about logistics operations.	0.86
	RTDI4	Data from logistics activities can be integrated with the virtual model.	0.78
	RTDI5	Real-time data integration improves visibility of logistics operations.	0.85
Bidirectional Connectivity	BC1	The Digital Twin continuously exchanges information with the physical logistics system.	0.82
	BC2	Information generated by the Digital Twin can support actions in physical operations.	0.87
	BC3	Our digital and physical logistics systems remain continuously connected.	0.84
	BC4	Changes in physical operations are reflected in the Digital Twin.	0.76
	BC5	Digital Twin outputs can be used to support operational decisions.	0.86
Virtual Representation & Simulation	VRSC1	The Digital Twin accurately represents important logistics processes.	0.83
	VRSC2	Our Digital Twin can simulate different logistics operating conditions.	0.89
	VRSC3	We can evaluate alternative logistics scenarios using the Digital Twin.	0.86
	VRSC4	Digital simulation helps identify potential logistics bottlenecks.	0.75
	VRSC5	The Digital Twin helps evaluate operational changes before implementation.	0.88
Data Analytics & Predictive Capability	DAPC1	Our Digital Twin analyzes operational data to identify logistics patterns.	0.85
	DAPC2	Digital analytics support forecasting of logistics requirements.	0.90
	DAPC3	Our company uses Digital Twin data to identify potential operational problems.	0.87
	DAPC4	Analytics help predict changes in demand and logistics conditions.	0.79
	DAPC5	Predictive information supports proactive logistics decisions.	0.88
Operational Services & Decision Support	OSDC1	Digital Twin outputs support logistics planning and scheduling.	0.84
	OSDC2	The Digital Twin provides information useful for resource allocation.	0.87
	OSDC3	Digital Twin services support inventory-related decisions.	0.82
	OSDC4	Managers use Digital Twin outputs when making logistics decisions.	0.89
	OSDC5	Digital Twin services support coordination of material flows.	0.77

Construct	Item	Statement	Loading
Logistics Operations Efficiency	LOE1	Our logistics activities are completed with minimal unnecessary waiting time.	0.82
	LOE2	Our logistics resources are used productively during operations.	0.86
	LOE3	Our company minimizes delays in internal material movement.	0.88
	LOE4	Logistics activities are performed within the required time.	0.84
	LOE5	Our logistics operations minimize unproductive movements or trips.	0.74
	LOE6	Material flows between operational stages are efficiently coordinated.	0.87
	LOE7	Our logistics operations minimize downtime and idle periods.	0.85
	LOE8	Overall logistics activities achieve efficient use of available time and resources.	0.91

4.3 Reliability and Convergent Validity

The reliability and convergent validity results are presented in **Table 4**. All constructs achieved satisfactory levels of internal consistency reliability. Cronbach's Alpha values ranged from 0.88 to 0.93, while rho_A values ranged from 0.89 to 0.94. Composite Reliability values ranged from 0.91 to 0.94, exceeding the recommended threshold of 0.70.

The results therefore indicate a high degree of internal consistency among the indicators associated with each construct. Furthermore, all Average Variance Extracted (AVE) values exceeded the minimum recommended level of 0.50, ranging from 0.66 to 0.72. This provides evidence of adequate convergent validity and indicates that each construct explains a substantial proportion of the variance in its corresponding indicators. The relatively high reliability coefficients across the constructs indicate that the measurement items consistently capture the intended dimensions of Digital Twin Technology and Logistics Operations Efficiency. At the same time, the AVE results confirm that the constructs explain more than half of the variance in their respective indicators.

4.4 Discriminant Validity

Discriminant validity was assessed using the Heterotrait–Monotrait (HTMT) ratio. The results presented in Table 4 indicate that all HTMT values remained below the conservative threshold of 0.85. The highest observed value was 0.82, indicating that although the five dimensions of Digital Twin Technology are conceptually related, they remain empirically distinguishable. This finding is particularly important for the current study because the dimensions represent interconnected but distinct technological capabilities. Real-time data integration concerns the continuous availability and synchronization of operational information, whereas bidirectional connectivity focuses on interaction between the physical and virtual environments. Similarly, virtual representation and simulation emphasize digital modeling and scenario evaluation, while data analytics and predictive capability concern the transformation of operational data into predictive insights. Operational services and decision support, in turn, reflect the use of digital outputs in actual managerial and operational decisions, **Table 5**.

4.5 Structural Model Assessment

Following the confirmation of the measurement model, the structural model was evaluated to examine the proposed relationships between the five dimensions of Digital Twin Technology and Logistics Operations Efficiency. The assessment focused on the coefficient of determination (R^2), predictive relevance (Q^2), effect sizes (f^2), path coefficients, and model fit.

The results indicate that the structural model explains a substantial proportion of the variance in Logistics Operations Efficiency. The R^2 value was 0.68, indicating that the five dimensions of Digital Twin Technology jointly explain approximately 68% of the variance in Logistics Operations Efficiency.

The Q^2 value was 0.46, which is greater than zero and therefore indicates satisfactory predictive relevance of the model for the endogenous construct. The model also demonstrated acceptable fit, with an SRMR value of 0.056 and an NFI value of 0.90. Taken together, these results suggest that the proposed model possesses satisfactory explanatory and predictive capabilities and provides an appropriate basis for testing the hypothesized relationships, **Table 6**.

The R^2 value of 0.68 represents substantial explanatory power, suggesting that Digital Twin capabilities collectively provide a strong explanation for variations in logistics operations efficiency among the sampled food manufacturing companies.

4.6 Hypotheses Testing

The results of hypothesis testing are presented in Table 6. The analysis was performed using bootstrapping with 5,000 subsamples to assess the statistical significance of the estimated path coefficients. The results indicate that all five dimensions of Digital Twin Technology have positive and statistically significant relationships with Logistics Operations Efficiency, although the magnitude of their effects differs across dimensions, **Table 7**.

H1: Real-Time Data Integration → Logistics Operations Efficiency

The findings show that Real-Time Data Integration has a positive and statistically significant effect on Logistics Operations Efficiency ($\beta = 0.24$, $T = 3.87$, $p < 0.001$). Therefore, H1 is supported.

This result indicates that food manufacturing companies with stronger capabilities to integrate and continuously update operational data tend to achieve higher logistics efficiency. The finding suggests that real-time access to information concerning inventory, material flows, resources, and logistics activities can improve operational visibility and reduce information-related delays.

H2: Bidirectional Connectivity → Logistics Operations Efficiency

Bidirectional Connectivity also demonstrates a positive and statistically significant relationship with Logistics Operations Efficiency ($\beta = 0.18$, $T = 2.96$, $p = 0.003$), supporting H2.

Although the coefficient is lower than those observed for some of the other dimensions, the significant relationship indicates that the continuous interaction between physical logistics operations and the virtual environment contributes to operational efficiency. This suggests that the ability to transmit information between the physical system and the Digital Twin can facilitate faster responses and better coordination of logistics activities.

H3: Virtual Representation and Simulation → Logistics Operations Efficiency

The results indicate a positive and statistically significant effect of Virtual Representation and Simulation Capability on Logistics Operations Efficiency ($\beta = 0.21$, $T = 3.42$, $p = 0.001$). Therefore, H3 is supported.

The finding suggests that companies capable of accurately representing logistics processes and evaluating alternative scenarios through simulation are better positioned to identify bottlenecks, assess operational alternatives, and improve the allocation of logistics resources.

H4: Data Analytics and Predictive Capability → Logistics Operations Efficiency

Data Analytics and Predictive Capability produced the strongest direct effect among the five dimensions ($\beta = 0.27$, $T = 4.51$, $p < 0.001$), providing strong support for H4.

This result indicates that the ability to transform operational data into analytical and predictive information is particularly important for logistics efficiency. Predictive capabilities may allow food manufacturing companies to anticipate demand changes, identify potential bottlenecks, estimate resource requirements, and reduce the likelihood of delays and unnecessary logistics activities.

H5: Operational Services and Decision-Support Capability → Logistics Operations Efficiency

Operational Services and Decision-Support Capability also demonstrated a positive and statistically significant effect on Logistics Operations Efficiency ($\beta = 0.22$, $T = 3.61$, $p < 0.001$). Accordingly, H5 is supported.

The result indicates that the operational value of Digital Twin technology is strengthened when its analytical and simulation outputs are transformed into actionable information supporting scheduling, resource allocation, inventory management, and material-flow decisions.

Overall, the hypothesis-testing results indicate that all five dimensions of Digital Twin Technology significantly contribute to Logistics Operations Efficiency. Among the five dimensions, Data Analytics and Predictive Capability demonstrated the strongest direct effect, followed by Real-Time Data Integration, Virtual Representation and Simulation Capability, Operational Services and Decision Support, and Bidirectional Connectivity.

4.7 Effect Size Analysis

To complement the significance testing, effect sizes were assessed using f^2 to determine the substantive contribution of each Digital Twin dimension to Logistics Operations Efficiency.

The effect-size results indicate that the dimensions do not contribute equally to the explanatory power of the structural model. Data Analytics and Predictive Capability demonstrates the largest incremental contribution ($f^2 = 0.13$), consistent with its relatively stronger path coefficient. Real-Time Data Integration represents the second-largest contribution ($f^2 = 0.09$), followed by Virtual Representation and Simulation ($f^2 = 0.08$).

Bidirectional Connectivity has the smallest incremental effect ($f^2 = 0.05$), although its effect remains statistically significant. These findings suggest that while all five dimensions are relevant to logistics efficiency, analytical and predictive capabilities may have a comparatively greater practical contribution to explaining differences in logistics performance, **Table 8**.

4.8 Overall Effect of Digital Twin Technology on Logistics Operations Efficiency

In addition to examining the five dimensions independently, a separate structural model was estimated to assess the overall effect of Digital Twin Technology on Logistics Operations Efficiency. In this analysis, Digital Twin Technology was treated as an integrated higher-order construct encompassing Real-Time Data Integration, Bidirectional Connectivity, Virtual Representation and Simulation Capability, Data Analytics and Predictive Capability, and Operational Services and Decision-Support Capability.

The results demonstrate a strong positive and statistically significant relationship between the overall Digital Twin Technology construct and Logistics Operations Efficiency ($\beta = 0.72$, $T = 14.86$, $p < 0.001$). Therefore, H6 is supported, **Table 9**.

The overall model produced an R^2 value of 0.52, indicating that the integrated Digital Twin Technology construct explains approximately 52% of the variance in Logistics Operations Efficiency when considered as a single higher-order technological capability. The corresponding Q^2 value was 0.35, indicating satisfactory predictive relevance.

The relatively strong path coefficient indicates that Digital Twin Technology, when considered as an integrated capability rather than as isolated technological components, has a substantial positive association with logistics operations efficiency. This finding complements the dimension-level analysis and provides empirical support for the overall proposition underlying the study.

Table 4. ***Reliability and Convergent Validity***

Construct	**CR**	**rho_A**	**(rho_c)**	**AVE**
Real-Time Data Integration	0.90	0.91	0.93	0.71
Bidirectional Connectivity	0.89	0.90	0.92	0.70
Virtual Representation & Simulation Capability	0.91	0.92	0.93	0.73
Data Analytics & Predictive Capability	0.91	0.92	0.94	0.75
Operational Services & Decision-Support Capability	0.90	0.91	0.93	0.72
Logistics Operations Efficiency	0.93	0.94	0.94	0.68

Note: All reliability coefficients exceed 0.70, and all AVE values exceed 0.50, indicating satisfactory internal consistency and convergent validity.

Table 5. HTMT Discriminant Validity

Construct	**RTDI**	**BC**	**VRSC**	**DAPC**	**OSDC**	**LOE**
Real-Time Data Integration (RTDI)	—					
Bidirectional Connectivity (BC)	0.76	—				
Virtual Representation & Simulation (VRSC)	0.72	0.78	—			
Data Analytics & Predictive Capability (DAPC)	0.79	0.74	0.81	—		
Operational Services & Decision Support (OSDC)	0.73	0.77	0.80	0.82	—	
Logistics Operations Efficiency (LOE)	0.68	0.65	0.72	0.76	0.74	—

Note: The highest HTMT value is 0.82, which is below the conservative threshold of 0.85, supporting discriminant validity.

Table 6. Structural Model Assessment

Endogenous Construct	**R^2**	**Q^2**
Logistics Operations Efficiency	0.68	0.46

Model Fit	**Value**

SRMR	0.056
NFI	0.90

Table 7. Results of Hypotheses Testing

Relationship		β	T-value	P-value
H1	Real-Time Data Integration → Logistics Operations Efficiency	0.24	3.87	<0.001
H2	Bidirectional Connectivity → Logistics Operations Efficiency	0.18	2.96	0.003
H3	Virtual Representation & Simulation → Logistics Operations Efficiency	0.21	3.42	0.001
H4	Data Analytics & Predictive Capability → Logistics Operations Efficiency	0.27	4.51	<0.001
H5	Operational Services & Decision Support → Logistics Operations Efficiency	0.22	3.61	<0.001

Table 8. Effect Size (f^2)

Relationship	f^2	Effect
Real-Time Data Integration → Logistics Operations Efficiency	0.09	Small
Bidirectional Connectivity → Logistics Operations Efficiency	0.05	Small
Virtual Representation & Simulation → Logistics Operations Efficiency	0.08	Small
Data Analytics & Predictive Capability → Logistics Operations Efficiency	0.13	Medium
Operational Services & Decision Support → Logistics Operations Efficiency	0.07	Small

Table 9. Overall Effect of Digital Twin Technology on Logistics Operations Efficiency

Relationship	β	T-value	P-value	Decision
Digital Twin Technology → Logistics Operations Efficiency	0.72	14.86	<0.001	Supported

Endogenous Construct	R^2	Q^2
Logistics Operations Efficiency	0.52	0.35

5.Discussion

Results of this study confirm that there is a positive relationship between DTT and LOP in food manufacturing companies in Saudi Arabia has been proven in the light of empirical data. In general, the outcomes are in line with this key research question: What is the value of Digital Twin for operations is not derived from or inspired by a single technological functionality but rather from complementary digital capabilities. Digital Twin Technology's overall effect on Logistics Operations Efficiency was positive and statistically significant ($\beta = 0.72$, $T = 14.86$, $p < 0.001$), and the model explained 52% of the variance in Logistics Operations Efficiency. This is in line with the concept of the Digital Twins as a unified system comprising a combination of physical objects, virtual models, data, communication, analytics, and services for monitoring, analyzing, predicting, and optimizing (Qi et al., 2019; Tao et al., 2019). It also buys empirical evidence to support the Resource Based View (RBV) which suggests that value is added with technology as long as the organization uses the technology in some of their processes and builds a capability that increases the performance (Wu et al., 2006). Therefore, the results challenged the typical conceptual and application-oriented literature on Digital Twins and showed statistical evidence of its relationship to logistics efficiency in an empirical setting of a food manufacturing value chain.

The results for Real-Time Data Integration on Logistics Operations Efficiency ($\beta = 0.24$, $T = 3.87$, $p < 0.001$) support H1 and this finding is consistent with the importance of synchronizing operational data with the virtual environment for the effectiveness of Digital Twins. For maintaining convergence between physical and virtual domains, the research by Qi et al. (2019) attends to sensor, operational and historical data besides digital models and analytical tools, while Tao and Zhang (2017) put forward continuous data exchange as a prerequisite for maintaining convergence between the physical and virtual domains. According to the present finding this can be applicable in Saudi food manufacturing, and can be used to track the availability of information concerning the inventory, movement of the materials, resources, orders and transportation of the food massive in a timely manner for the purpose of reducing information gaps and identifying deviations in the food operations in a timely manner. The result also aligns with the results in Kaiblinger and Woschank (2022) as well as with the results of Huang et al. (2026), who found that improved information visibility and data flows can improve the end-to-end performance of food supply chains in terms of inventory, delays, and order fulfillment.

But after the bidirectional connection, the impact was positive and statistically significant with Logistics Operations Efficiency ($\beta = 0.18$, $T = 2.96$, $p = 0.003$) was supported. Despite being the lowest of the five direct relationships, its importance indicates the importance of connecting the physical and virtual reality in logistics and this is an important part of Digital Twin functions. The finding is in line with Tao and Zhang (2017), Qi et al (2019) and others, who suggest that one of the key features of the Digital Twin technology is the ability to communicate and interact between the physical world and the virtual world. It is also consistent with Leng et al. (2021), who showed the benefits of the real-time integration of the warehouse data with a cyber model, for optimization and simulation, and with Agalianos et al. (2021), who underlined the benefits of using operational data and simulation for monitoring and decision making. The relative coefficient is smaller, suggesting that mere connection is not enough to produce any significant amount of efficiency unless that information is subsequently followed up with further analysis and decision making.

The results also confirmed the H3 hypothesis, which Virtual Representation and Simulation Capability has a positive and significant influence on Logistics Operations Efficiency ($\beta = 0.21$, $T = 3{,}42$, and $p = 0{,}001$). This finding aligns with the argument put forward by Kritzinger et al. (2018) and Tao et al. (2019) that Digital Twin value extends beyond providing a digital representation to analyzing the behavior of a system and testing out various scenarios. It is also in line with previous studies by Kaiblinger and Woschank (2022) and Leng et al. (2021), who have highlighted the use of simulation as a way of highlighting bottlenecks, testing solutions and optimising the allocation of resources. The result is incredibly pertinent to food manufacturing, when the operation changes, such as in scheduling, material transportation, storage, or resource allocation, it can impact on a time-sensitive product. This means that evaluations of alternative decisions prior to any physical implementation can therefore be beneficial and minimize the need for trial and error and improve logistics flow.

Among the five dimensions, Data Analytics and Predictive Capability demonstrated the strongest direct effect on Logistics Operations Efficiency ($\beta = 0.27$, $T = 4.51$, $p < 0.001$), providing strong support for H4. This result matches the conceptualization of Big Data Analytics as an information processing ability (Chen et al., 2015) which creates knowledge, lessens uncertainty and enables better decision-making. It also validates what Qi et al. (2019) found—that modelling, prediction and optimization are crucial functions of Digital Twin. The higher coefficient indicates that, in the context of the Saudi food manufacturing industry, the capability of converting basic and operational information to information of prediction may play a significant role in improving the food logistics industry efficiency. This feature enables organizations to shift from a reactive strategy to a proactive one, predicting demand fluctuations, possible bottlenecks, need of resources and delays. This is consistent with Huang et al. (2026) and Maheshwari et al. (2023b), who found that their analytical use of Digital Twin helped improve inventory management, planning, scheduling, lead time, and productivity.

Additionally, any of the hypotheses had operational services ($\beta = 0.22$, $T = 3.61$, $p > 0.001$) and decision-support capability ($\beta = 0.23$, $T = 3.65$, $p > 0.001$) as significant positive contributors to Logistics Operations Efficiency. This discovery shows that operational value of the Digital Twins cannot be seen just in the collection and analysis of data but also in the operational decisions that are taken, made by the help of the digital outputs. Qian et al. (2019) introduced the concept service as key elements of the Digital Twin architecture, Tao and Zhang (2017) pointed out the importance of interaction, control and intelligent management. The findings are also confirmed by Kauke et al. (2021); Leng et al. (2021); and Ashrafian and Pedersen (2023) who used a Digital Twin in application during operation monitoring, scenario analysis and decision support. To view this result from the RBV perspective, this result builds on the RBV argument that IT infrastructure contributes to value creation when integrated in an organizational process and activated as an operational capability (Wu et al., 2006).

These all come out as a collective implication: First, the study builds on RBV by showcasing how the Digital Twin technology could be understood as a package of related technological capacities that can all together add to the value of operations. Second, the findings are consistent with the dynamic-capability logic proposed by Teece et al. (1997) inasmuch as real-time integration, analysis, simulation and decision support allow organizations to gain a sense of operational change, consider alternatives and reconfigure resources. Third, a contribution to Digital Twin research is the shift of the study's approach from conceptual architectures, individual case applications to quantitative evidence of how Digital Twin capabilities are related to logistics efficiency. Also, the results reveal a degree of empirical separability of the dimensions but at the same time an implied capability of technology that is integrated.

The study provides practical implications to the managers of food manufacturing companies in Saudi's Arabia. Investment in Digital Twin technology should not only be in producing a virtual model of physical operations. Rather, it is desirable to plan an integrated architecture that will enable businesses to have continuous data moving between these different disciplines, reliable physical–virtual connections, simulation flexibility, predictive analytics, and decision supporting services. Managers may find reinforcing the direct impact of Data Analytics and Predictive Capability most beneficial, especially regarding inventory, demand, resource needs and possible logistics issues. Significant contributions from all five dimensions, however, also means that if any one dimension is neglected then it will be difficult to reap the benefits of whole Digital Twin technology. These data are especially relevant for Saudi Arabia as part of its ongoing efforts to bolster the food security, industrial competitiveness, and logistics supply chain for people and goods in a digital age, as set forth in Vision 2030 and the National Industrial Development and Logistics Program.

Although these are the contributions made, there are a number of limitations to the study. Firstly, its cross-sectional design has restricted the causal conclusions, or to see how its capabilities of Digital Twin and efficiency of logistics will change over time. Second, the study's results are dependent on perceived opinions by 195 respondents and the respondents may have responded to the questions in a manner that is susceptible to common method bias and subjective operational efficiency evaluation. A third limitation was that the study concentrated on the food manufacturers in Saudi Arabia and this could restrict the applicability of the results to other manufacturing sectors and/or other national settings. Fourth, the model addresses five technological aspects, but these do not reflect organizational readiness to adopt the Digital Twin, the implementation costs, the capabilities of employees to implement it, or interoperability issues, or external environmental factors that may affect the adoption and results of the Digital Twin. To address these limitations, future research can be implemented using a longitudinal study, a quantitative measure of operational performance, a larger sample size and diverse samples, and comparative studies between industries and countries. This type of research could also shed more light on the situation in which the Digital Twin capabilities offer the most operational value and on the time evolution of their benefit.

6. Conclusion

Accordingly, this study concludes that the Digital Twin Technology (DTT) is a technological capability when integrated can make a significant contribution towards the efficiency of logistics operations in food manufacturing companies in the Kingdom of Saudi Arabia (KSA). Considering the ongoing rapid change in the manufacturing and logistics context in today's Fourth Industrial Revolution, the study aimed to go beyond the conceptual debate about the potential of the Digital Twin and to empirically analyze the correlation between the primary capabilities of the Digital Twin and the efficiency of logistics operations. This study encompassed the following pivotal factors of Digital Twin Technology, Real-Time Data Integration, Bidirectional Connectivity, Virtual Representation and Simulation Capability, Data Analytics and Predictive Capability and Operational Services and Decision-Support Capability.

Empirical results obtained from the 195 respondents working in food manufacturing companies in Saudi Arabia support the five hypotheses by showing that all five technology dimensions: Digital, Digital Support, and Digital Usage, were positively and statistically significant with the logistics operations efficiency. Of these dimensions, Data Analytics and Predictive Capability has the strongest direct effect. These can be of great value in the area of demand forecasting, early detection of potential issues, resource planning and delay reduction due to the transformation of operational data to analytical and predictive information. These also showed great positive effects and were also confirmation of not only how diverse applications of digital technology benefit the logistics in question, but also how complementary – and therefore essential for logistics efficiency – they are.

Overall, the study clearly showed effective integrated Digital Twin Technology with Logistics Operations Efficiency, with a path coefficient of $\beta = 0.72$ and a statistically significant effect at $p < 0.001$. The result provides the supporting argument for the study's central idea, namely that the operational value of a Digital Twin cannot be solely based on the production of a virtual copy of a physical system, but instead relies instead upon integration of data, connectivity, simulation, analysis, and operational services, done in unison, which will help support real decisions and actions in the real world. The overall model accounted for 52% of the variance in Logistics Operations Efficiency, which is substantial.

The results bring some theory support to the Resource Based View (RBV), which suggests that technology alone does not create value in the organization. Value, on the other hand, is created when technology tools are embedded within the processes of organizations and become functional. The findings also support the idea of dynamic capabilities since the ability of reacting to changing conditions, reconfigure resources and processes is better performed by making use of real-time data, data analysis, simulation and decision support functions. On a practical level, the indicates that Saudi food manufacturing companies can benefit from Digital Twin Technology as a means of improving material flows, reduce waiting and delays, optimize the use of resources, and plan, schedule and monitor the factories to make decision making. This is crucial for the Saudi government's initiative to boost the capabilities of Saudi industries, food security, logistics, and digitization in line with Saudi Vision 2030. The study results present empirical evidence that the adoption of actions linked to Integrated investment into Digital Twin Capabilities can be a concrete solution for achieving efficiency in the logistics operations of food manufacturing companies, in order to support their competitiveness in the Kingdom.

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