The Mediating Role of Supply Chain Transparency and Resilience in the Relationship between Digital Twins and Sustainable Performance: Applied to the Egyptian Manufacturing Industry [1]

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ABSTRACT

This study explores the effect of digital twins (DT) on the sustainability of supply chains, emphasizing resilience and transparency. Digital twins, as real-time virtual representations, enhance supply chain sustainability efficiency by improving coordination, visibility, adaptability, and forecasting accuracy. The integration of DT with artificial intelligence, resilience, and transparency enables real-time monitoring, optimizing resource utilization, and mitigating disruptions. Using structural equation modeling (SEM), the study looks at how DT, supply chain transparency (SCT), resilience (SCR), and sustainability performance are connected in Egypt's manufacturing sector. Primary data were collected through surveys administered to a sample of 248 managers from industrial companies in Egypt. Findings indicate that DT significantly enhances SCT and SCR, which in turn positively influence sustainability. Additionally, SCT and SCR mediate the relationship between DT and sustainability performance, reinforcing their role in achieving long-term supply chain stability. The research provides a conceptual framework and empirical insights into the adoption of digital technology (DT) for sustainable industrial operations. Future studies should explore broader applications of DT across industries, integrating emerging technologies like blockchain and artificial intelligence to further enhance supply chain efficiency and sustainability.

Keywords: *Digital Twins, Sustainable Performance, Supply Chain Transparency and Supply Chains.*

I. INTRODUCTION

Over the past decade, significant technological advancements have been made in Industry 4.0, artificial intelligence, blockchain, 3D printing, and digital twins. Sustainability in manufacturing and service delivery has also gained attention, particularly in environmental protection (Singh & Singh, 2023). Digitization is being transitioned to society for benefits like faster information access, improved customer experience, increased productivity, better decision-making, reduced costs, and increased safety (Khan, Babar, Sharif, Iqbal, & Khan, 2021; Rosin, Proksch, Stubner, & Pinkwart, 2020; Sabbagh, Friedrich, El-Darwiche, Singh, Ganediwalla, & Katz 2012). Digital twins are gaining prominence in supply chain management due to their capacity to enhance performance of supply chain in some ways (Rauniyar, Hagos, Jha, Håkegård, Bagci, Rawat, & Vlassov, 2023). Digital twins can demonstrate the operational efficiency of a supply chain in real-time (Ivanov, 2023). Managers can identify bottlenecks, manage inventory, and oversee item movement (Bag, Gupta, & Kumar 2021). Digital twins enhance transparency and accountability, facilitating more effective and efficient collaboration among supply chain stakeholders (Rana & Daultani, 2023; Taghizadeh & Hajhosseini, 2021) Supply Chain Transparency (SCT) means the revelation of operational data to consumers, owners, and the community (Sodhi & Tang, 2019). In addition to enhancing operational efficiency and decision-making, promoting transparency in the SC is intended to develop the firm's reputation and ensure compliance. The integration of sustainability and resilience into supply chain design and management is a recent paradigm, aiming to ensure seamless operations and mitigate future failures in manufacturing supply chains (Owida, Galal, & Elrafie, 2022). Current disruptions are causing the forfeiture of sustainability objectives for supply networks (Amindoust, 2018). Supply chain resilience refers to the supply chain's ability to anticipate and respond to unforeseen events, disruptions, and recover by maintaining operational continuity and governance over structure and function (Ponomarov & Holcomb, 2009).

Digital Twins (DT) are being investigated as a means to improve supply chain efficiency and transparency (Attaran & Celik, 2023). Through process optimization and the identification of improvement areas, DT can enhance efficiency and production. Organizations are implementing digital twins to visualize and simulate operations (Singh & Singh, 2023). The amalgamation of digital twins with artificial intelligence, cloud computing, speech functionalities, and augmented realities is anticipated to enhance the accessibility of the technology (Attaran & Celik, 2023). The proposed technique is to reduce interruptions and delays, hence enhancing the supply chain's resilience and

adaptation to evolving conditions (Bianco, Bueno, Godinho, Latan, Ganga, Frank, & Jabbour, 2023). Digital Twins can enhance a robust supply chain through predictive and prescriptive analytics, essential for the competitiveness of the industrial industry (Abbasi, Zahmatkesh, Bokhari, & Hajiaghaei-Keshteli, 2023). Digital Twins improves characteristics including coordination, visibility, adaptability, and forecasting accuracy (Kamble, Gunasekaran, Parekh, Mani, Belhadi, & Sharma, 2022). The program replicates the production environment utilizing data, assisting owners in determining best strategies for enhanced productivity, precision, and cost efficiency. Digital technology can markedly enhance supply chain performance by augmenting visibility, optimizing efficiency, refining risk management, and promoting collaboration (Belhadi, Kamble, Jabbour, Gunasekaran, Ndubisi, & Venkatesh, 2021).

DT can enhance transparency in supply chain. Therefore, it is essential to comprehend Digital twins (DT), its correlation with Supply Chain transparency (SCT), and the effects of DT adoption on sustainable performance. The convergence of Digital twins and Supply Chain transparency can yield distinctive insights for attaining sustainable performance in supply chain systems. Research indicates that Digital technologies enhance transparency by facilitating real-time oversight of production processes, demand patterns and inventory levels (Attaran & Celik, 2023). The interdependent relationship between digital twin adoption and supply chain technology is examined about enhanced responsiveness to disruptions and fluctuations in demand. The report offers insights on attaining judicious transparency and enhancing the resilience of the supply chain against external uncertainty. This study expands the discourse by examining the links between Digital twins and SCT to attain a sustainable performance system. this research aims to measure the influence of digital twins on sustainability performance and identify the mediating role of SCR and SCT by focusing on Egypt's manufacturing industry.

2. RESEARCH PROBLEM

The industrial business environment is experiencing rapid transformation due to digitalization, with digital twins being one of the emerging technologies contributing to operational efficiency and data-driven decision-making. However, the relationship between the implementation of digital twins and sustainable performance within supply chains remains insufficiently explored, particularly in the context of the Egyptian industrial sector. This raises the question of potential mediating factors, such as supply chain transparency and resilience, which are fundamental to ensuring adaptability and competitiveness in dynamic business environments.

The research problem focuses on investigating the mediating role of supply chain transparency and resilience in explaining the relationship between digital twins and sustainable performance in the Egyptian industrial sector, particularly in light of the economic and technological challenges facing the industry there. This study seeks to answer the following research questions:

1. To what extent do digital twins influence sustainable performance in the Egyptian industrial sector?

2. How do digital twins impact supply chain transparency within the Egyptian industrial sector?

3. What is the effect of digital twins on supply chain resilience in the Egyptian industrial sector?

4. To what extent do supply chain transparency influence sustainable performance in the Egyptian industrial sector?

5. To what extent do supply chain resilience influence sustainable performance in the Egyptian industrial sector?

6. To what extent does supply chain transparency enhance the relationship between digital twins and sustainable performance?

7. How does supply chain resilience influence the relationship between digital twins and sustainable performance?

Digital twins enable industrial organizations to simulate and analyze operational processes in real time, enhancing predictive capabilities and supporting data-informed decisions. However, leveraging this technology does not guarantee improved sustainable performance unless it is integrated with strategic and organizational enablers within the supply chain.

Studying these factors in the Egyptian industrial setting is especially important because the industry is facing challenges with digital transformation and there is uncertainty about how ready supply chains are to use advanced technologies. Achieving sustainable performance is no longer merely a strategic option but a necessity imposed by growing environmental, social, and economic obligations.

3. THEORETICAL FRAMEWORK

3.1 Digital Twins

The concept of "twin" has seen substantial evolution since the 1960s, with implementations across several fields. In manufacturing, (DT) is an actual virtual representation of processes, persons, products, and assets that is updated as the physical counterpart evolves (Catalano, Iacopetta, Ceramella, Scumaci, Giuzio,

Saturnino, Aquaro, Rosano, & Sinicropi, 2022; Su, Pang, Tao, Shao, & Umar, 2022). Design Thinking enhances efficiency in product design, production planning, and maintenance (Park, Lee, & Kim, 2020). Comprehending the utilization of DT is essential for a comprehensive grasp of its applications (Song, Zhang, Tang, Zhu, Wang, & Nie, 2024). Digital twins replicate industrial systems through data utilization to enhance management and optimize productivity, efficiency, and cost advantages (Gill, Xu, Patros, Wu, Kaur, Kaur, Fuller, Singh, Arora, &Parlikad, 2024). They facilitate precise, sustainable, and adaptable manufacturing processes (Kamble et al., 2022). Manufacturers employ IoT-based robotic systems to automate production lines, simultaneously generating digital information. Digital information is essential in high-productivity industrial environments, where minor enhancements in productivity, product quality, and equipment reliability are significant (Andreasson, Karabag, Simonsson, Agarwal, 2024; Senna, Roca, & Barros, 2023).

Digital Twins were employed to replicate spacecraft circumstances, investigate solutions, and forecast outcomes, which were essential in planning, design, operation, and management (Liu, Wu, Wan, & Xu, 2024). Digital Twins have been characterized in multiple manners, encompassing a virtual representation of physical assets, a collection of virtual information constructs (Glaessgen & Stargel, 2012; Lee, Lapira, Bagheri, & Kao 2013). DT can be employed for the design, modelling, visualization, testing, and implementation of new concepts without interrupting the existing process. Digital Twin comprises three fundamental layers: the physical layer encompasses tangible information, the communication layer incorporates data transmission mechanisms, and the digital layer comprises computational and simulation methodologies (Far & Rad, 2022; Lv, Qiao, Li, Yuan, & Wang, 2022; Zheng, Lu, & Kiritsis, 2022). Data-driven techniques are increasingly utilized in Supply Chain Management (SCM), an essential field for enterprises and supply chain management Supply chain management guarantees cost effectiveness, customer satisfaction, risk mitigation, quality assurance, and strategic coherence (Siddiqui, Altekar, Kautish, Fulzele, Kulkarni, Siddiqui, & Bashir, 2023).

3.2 Supply Chain Transparency

Supply chain transparency (SCT) is a concept that involves revealing information to external stakeholders without loss, noise, delay, and distortion (Sodhi & Tang, 2019). Supply Chain transparency (SCT) is a strategy methodology aimed at enhancing operational efficiency, mitigating risks, and ensuring regulatory compliance (Sunny, Undralla, & Pillai, 2020). It has garnered attention in recent years owing to developments in information technology, regulatory compliance, and customer awareness (Sodhi & Tang, 2019). Nonetheless, its association with

these concepts remains ambiguous (Busse, Kach, & Wagner, 2017; Mohamed, Haddad, Barakat, & Rosi, 2023; Sharma, Srivastava, & Sharma, 2024). To attain SCT, mapping supply chain processes and employing Digital Twin tools can facilitate the monitoring of real-time operations (Sunny et al., 2020). An enhanced comprehension of SCT is required for its efficacy. (Sodhi & Tang, 2019).

3.3 Supply Chain Resilience

Supply chain resilience has become a significant importance for businesses, governments, and the community in the last two decades. (Cohen, Cui, Doetsch, Ernst, Huchzermeier, Kouvelis, Lee, Matsuo, & Tsay, 2022; Mubarik, & Khan, 2024) identified three dimensions of resilience: readiness, agility, and recovery. Preparedness denotes a supply chain's capacity to manage disruptions, its agility to swiftly adjust to alterations, and its recovery to rapidly rebound following disturbances. These aspects are essential for sustainability, as they guarantee the satisfaction of current and future requirements. (Owida et al., 2022). resilience is viewed as a dynamic process that requires agility, addictiveness, and flexibility to cope with and recover from disruptions.

3.4 Sustainability Performance

Sustainability performance entails prioritizing sustainability, allocating resources, establishing explicit objectives, monitoring and reporting, integrating innovative technology, and acknowledging it as both a responsibility and an opportunity for growth (Abougalil, Gamal Abd Elasser, Gamil, & Negi, S. 2025; Neri, Cagno, Lepri, & Trianni 2021). Sustainable business methods seek to enhance environmental, social, and economic results, taking into account environmental and social burdens (Markman & Krause, 2016). Organizations in supply chains strive to harmonize economic prosperity, social justice, and environmental conservation, thereby favorably impacting sustainable development objectives. Suppliers, focal companies, distributors, retailers, and customers are interlinked via information, materials, and finances, with focal companies potentially liable for their environmental and social performance (Seuring & Müller, 2008). Organizational learning and transformation, along with education for sustainability discourse, are essential for the effective execution of sustainability projects. Particular relational attributes, like elevated transaction volumes, enduring relationships, and strategic alliances, enhance sustainability performance (Naffin, Klewitz, & Schaltegger, 2023).

4. HYPOTHESES DEVELOPMENT AND CONCEPTUAL FRAMEWORK

Digital twins enhance sustainable manufacturing operations by offering a data-intensive framework for actual monitoring, simulation, and forecasting of work processes. (Kamble et al., 2022). This enhances supply chain performance and sustainability also, Digital twins provide a virtual representation of the complete supply chain, encompassing plants, warehouses, and transportation links (Cimino, Negri, & Fumagalli, 2019). Analysis of information provides insights into the physical system's operation and potential enhancements. H3 is proposed:

H1. Digital twins enhance Sustainability Performance.

The integration of digital twins and supply chain transparency significantly improves organizations' capacity to optimize supply chain operations and make informed decisions. (Dolgui & Ivanov, 2020). DT generates virtual counterparts of tangible assets or procedures, facilitating instantaneous observation, evaluation, and modelling, it guarantees transparency by providing a comprehensive overview of commodity movement and management, identifying inefficiencies, risk mitigation, and improving quality control (Mubarik & Khan, 2024). H1 is proposed:

H2. Digital twins enhance Supply Chain Transparency.

The digital twin concept is an all-encompassing instrument that provides real-time surveillance, modelling, optimization, and precise predictions. (Ivanov et al., 2019). It represents every aspect of a product, from its atomic configuration to macroscopic morphology also digital twins can provide information equivalent to physical inspections and can mitigate disruptions in complex supply chains by identifying patterns and bottlenecks. They also enable firms to operate efficiently and adapt to evolving circumstances also digital twins enhance company preparedness and resilience in supply chain operations by promoting improved communication and coordination among stakeholders (Singh & Singh, 2023). H2 is proposed:

H3. Digital twins enhance Supply Chain Resilience.

Transparency in manufacturing supply chains is crucial for long-term success and positive outcomes (Patil & Pimpale, 2024). Transparent supply chains enable organizations to trace raw material sourcing, oversee production processes, and examine distribution networks, ensuring ethical practices also, this transparency improves risk management by revealing vulnerabilities and facilitating prompt interventions. supply chains improve brand reputation, appeal to environmentally conscious consumers, and adhere to changing rules,

leading to long-term sustainability (Naffin et al., 2023). The interplay between Supply Chain Transparency (SCT) and sustainable performance is essential for transforming the manufacturing sector into responsible, resilient, and profitable operations (Patil & Pimpale, 2024). H4 is proposed:

H4. Supply Chain Transparency (SCT) enhance Sustainability Performance.

Sustainable supply chain management (SCS) involves managing material, information, and capital flows, collaborating with companies, and considering economic, environmental, and social objectives (Seuring & Müller, 2008). Research has examined the intersection of supply chain sustainability, and resilience with literature categorized into three streams: adverse interactions, sequential perspectives, and positive interactions (Doetsch & Huchzermeier, 2024). Resilience and sustainability are distinct concepts, with resilience focusing on system dynamics and sustainability on natural capital preservation also, Miller and Engemann (2019) propose three mechanisms for enhancing resilience: averting sustainability-related shocks, expediting recovery from disruptions, and fostering customer goodwill through a sustainability-oriented approach. These studies highlight the importance of understanding the interplay between these concepts in achieving sustainable development. we can postulate the following hypothesis

H5. Supply chain Resilience enhance Sustainability Performance.

H6. Supply chain Transparency mediates in the interaction between digital twins and sustainability performance.

H7. Supply chain Resilience mediates in the interaction between digital twins and sustainability performance.

Digital twins are transformative technologies that enhance operational efficiency and sustainability, digital twins provide real-time monitoring and predictive analytics, which improve resource efficiency and reduce waste. Kritzinger, Karner, Traar, Henjes, and Sihn, (2018) explain that they enable proactive maintenance and process optimization, contributing to both environmental and economic sustainability. (Lee et al., 2015) highlight that incorporating digital twin technology into production systems results in decreased energy consumption and carbon emissions, thereby promoting sustainability. Overall, digital twins represent a powerful tool for achieving environmental and economic objectives. Digital twins are closely associated with supply chain transparency, as they offer a comprehensive digital representation of supply chain activities. According to Qi, Tao, Zuo, Zhao, and Zhang (2020) that digital twins enhance real-time visibility and facilitate efficient information exchange

among stakeholders. Zhong, Lu, and Kiritsis (2019) note that such transparency promotes collaboration and trust, which are essential for responsive and sustainable supply chain management. Furthermore, Leng, Jiang, Xu, Xu, and Liu (2021) highlight that digital twins allow stakeholders to access accurate and timely data across the supply network, making them a critical enabler of transparent supply chains. Digital twins have been found to enhance supply chain resilience by enabling rapid adaptability to disruptions, digital twins can simulate disruption scenarios and support the development of adaptive response mechanisms. (Ivanov et al., 2019) Similarly, Queiroz, Wamba, and Almeida (2020) argue that these technologies help supply chains anticipate and recover more effectively from unforeseen changes, and the provision of real-time system status improves decision-making agility, which is a critical element of resilient supply chain operations.

Transparency is crucial in promoting sustainable supply chains, as it aids stakeholders in monitoring and enforcing sustainable policies. It also enhances environmental and social performance, leading to improved sustainability outcomes. Furthermore, transparency is vital for effective risk management and adherence to sustainability norms, as highlighted by Seuring and Müller (2008). Supply chain resilience is closely linked to sustainability, as it enables organizations to adapt to environmental challenges and maintain long-term operations. Brandon-Jones, Squire, Autry, and Petersen (2014) highlight that resilient supply chains are better equipped to withstand disruptions while supporting the achievement of sustainability objectives. Christopher and Peck (2004) emphasize that resilient supply networks can absorb shocks and continue to function effectively, which is vital for sustainable performance. Furthermore, Wieland and Wallenburg (2013) argue that resilience facilitates sustainable practices by enabling swift responses to regulatory changes and market volatility, thereby supporting long-term sustainability. Guided by the existing literature, this study proposes the following conceptual structural model.

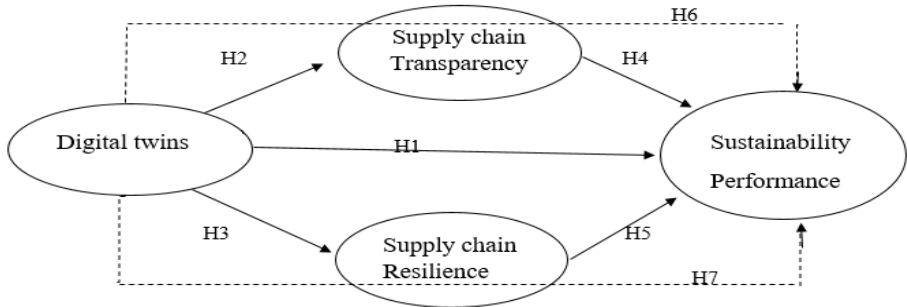The conceptual structural model is shown in Fig. 1.

Fig. 1. Theoretical framework

5. RESEARCH METHODOLOGY

This study aimed to examine the instruments by which the utilization of digital twin influences supply chain transparency, resilience, and sustainability performance. To evaluate the study's hypotheses, the researcher collected data from the industrial supply chain in Egypt, particularly from entities utilizing DT technologies for supply chain management.

A pre-test with ten supply chain management experts and five academics was conducted, incorporating their suggestions into the final survey. A glossary was provided to avoid confusion and participants' identities were kept confidential.

The study population consists of 65 large industrial companies in Egypt, defined by the Egyptian Federation of Industries as those with capital exceeding EGP200 million, across various sectors. The selection of these companies was based on their active adoption of digital twin technologies for supply chain management.

A purposive sampling approach was used to collect data from middle- and upper-level managers within these companies. We received 248 valid responses out of 400 distributed questionnaires, indicating a 62% response rate. This sample size is sufficient for robust statistical analysis using structural equation modelling (SEM), which ensures reliable and relevant findings.

The following industrial sectors were selected: Plastic & petrochemicals, electronics, food processing, and medical industries, as they represent some of the most digitally transformative sectors in Egypt, according to the Egyptian Federation of Industries. These sectors have practical applications of digital twin technology, particularly in production, quality control, and inventory management. Additionally, they are vital components of the Egyptian economy, and analyzing them gives helpful insights to industry decision-makers. Previous literature and preliminary communications conducted prior to the survey development further confirmed the relevance of these sectors to the study topic.

5.1. Data Collection Instrument

To collect data and test hypotheses, a survey was generated. It included four sections (digital twin, supply chain transparency, supply chain resilience, sustainability performance).

Digital twin: comprises nine items according to (Kamble et al., 2022; Singh & Singh, 2023).

Supply chain resilience: three items according to (Mubarik et al., 2021; Qader et al., 2022).

Supply chain transparency: four items according to (Dolgui & Ivanov, 2020; Wu & Yu, 2023).

Sustainability performance: four items according to (Wang, Yang, Yin, & Zhang, 2018; Zaid, Jaaron, Bon, & 2018). The study utilized a 5-point Likert scale to measure responses, with 1 indicating low effect and 5 indicating high effect, as detailed in table 1 for the main study.

Table 1: A summary of the characteristics of the sample

Demographic Variables	Criteria	Frequency	Percentage
Gender	Male	182	73.4 %
	Female	66	26.6%
Age	less than 30 years	45	18.1%
	From 30 to Less than 40	68	27.4%
	from 40 to less than 50	86	34.6%
	50years and more	49	19.8%
Functional Level	Head of Department	86	34.6%
	Director	79	31.9%
	General Director	51	20.5%
	Chairman	32	12.9%
Industrial Sector	Plastic &petrochemicals	43	17.1%
	Electronic manufacturer	68	27.4%
	Food processing	86	34.7%
	medical industry	38	15.3%
	Others	13	5.2%

Source: This research.

5.2 Data Analysis and Results

The study utilized structural equation modeling through AMOS to evaluate relationships, obtaining validity and reliability statistics and analyzing the structural model to uncover relationships. Before testing hypotheses, researchers ensure the reliability and validity of research variables through validity and reliability analysis. Validity is determined by the Average Variance Extracted (AVE), with a result greater than 0.5 indicating adequate validity. Factor loading and composite reliability are also assessed using Cronbach's Alpha, a commonly used test. A score between 0 and 1 indicates higher reliability, with a 0.7 or higher indicating adequate reliability. Table 2 shows acceptable reliability with Cronbach's alpha values exceeding 0.5, and overall composite reliability of 0.835, indicating strong consistency and reliability of the data.

Table 2: Validity and Reliability

Latent Variable/construct.	Item.	Factor Loading.	Composite Reliability.	Cronbach's Alpha	AVE.
	DT1	0.860			
	DT2	0.912			
	DT3	0.878			
	DT4	0.893			
Digital Twins (DT)	DT5	0.845	0.871	0.842	0.737
	DT6	0.830			
	DT7	0.902			
	DT8	.828			
	DT9	0.893			
	SCT1	0.871			
Supply chain Transparency (SCT)	SCT2	0.749	0.849	0.911	0.613
	SCT3	0.841			
	SCT4	0.751			
	SCR1	0.702			
Supply chain resilience (SCR)	SCR2	0.813	0.882	0.887	0.737
	SCR3	0.851			
	SP1	0.881			
Sustainability performance (SP)	SP2	0.841	0.891	0.914	0.686
	SP3	0.902			
	SP4	0.871			

Source: This research.

Table 2 presents the validity and reliability analyses for the latent constructs used in this study. All constructs demonstrated high reliability, exceeding the acceptable threshold of 0.7, indicating the instrument's consistency and stability. Convergent validity, evaluated through the Average Variance Extracted (AVE), confirmed strong associations with latent variables. Discriminant validity ensured conceptual distinction between constructs. The measurement scales used in this study exhibit satisfactory levels of validity and reliability, enhancing the credibility of the research findings and conclusions.

Table 3: Discriminate Validity.

	DT	SCT	SCR	SP
DT	0.871			
SCT	0.514	0.773		
SCR	0.581	0.581	0.881	
SP	0.659	0.551	0.519	0.858

Source: This research.

Table 3 presents the discriminant validity analysis for the latent constructs in this study, ensuring each is distinct from others. The Fornell-Larcker criterion was used to check if the constructs are different from each other, showing that the square root of the Average Variance Extracted (AVE) for each construct is higher than the correlation values between the constructs. All constructs (DT = 0.871, SCT = 0.773, SCR = 0.881, SP = 0.858) had square roots exceeding their respective correlations with other constructs, indicating excellent discriminant validity among the four latent variables. This confirms that the latent constructs measure distinct and independent concepts, which enhances the accuracy and reliability of the study model.

Table 4: Structural Equation Model Fit Indices

Chi-square / Degrees of Freedom (CMIN/DF)	Goodness of Fit Index (GFI)	Adjusted Goodness of Fit Index (AGFI)	Comparative Fit Index (CFI)	Root Mean Square Error of Approximation (RMSEA)
1.472	0.90	0.87	0.91	0.043

Source: This research.

Table 4 presents important results that suggest a good match between digital twins and sustainable performance. All path coefficients are statistically significant, highlighting the mediating role of supply chain transparency and resilience in the relationship. Specifically, the adjusted chi-square statistic divided by degrees of freedom (CMIN/DF) is 1.472, which falls within the acceptable range, indicating a good fit. The Goodness of Fit Index (GFI) is 0.90, and the Comparative Fit Index (CFI) is 0.91; both values are considered acceptable and indicate a satisfactory level of model fit. These indices are particularly useful for comparing model fit across studies with varying sample sizes, where higher values reflect better fit. The Root Mean Square Error of Approximation (RMSEA) is 0.043, which represents the amount of unexplained error in the model. This value is acceptable as it is below the commonly used threshold of 0.08 (8%), and smaller values indicate a better fit.

Overall, these fit indices collectively confirm the adequacy and quality of the estimated structural equation model.

5.3 Testing Research Hypotheses

Regression analysis is a statistical technique used in various fields like social, physical, biological sciences, business, and engineering to infer relationships among interrelated variables, making it the most widely used data analysis method. The research hypotheses were tested using structural equation modeling (SEM), as presented in Table 5 of the findings study.

Hypothesis	Path coefficient (β)	t-statistics	p-values	Results
H1. Digital twins enhance sustainability performance.	0.481	11.705	0.0031	Supported
H2. Digital twins enhance supply chain transparency.	0.538	8.356	0.001	Supported
H3. Digital twins enhance supply chain Resilience.	0.385	10.754	0.000	Supported
H4. Supply Chain Transparency (SCT) enhance sustainability performance.	0.452	10.658	0.0027	Supported
H5. Supply chain resilience enhance sustainability performance.	0.237	8.987	0.000	Supported
H6. Supply chain transparency mediates in the interaction between digital twins and sustainability performance.	0.413	9.621	0.0001	Supported
H7. Supply chain resilience mediates the relationship between digital twins and sustainability performance.	0.306	7.912	0.000	Supported

Source(s): Authors own work

The study presents a model based on digital twins, which significantly influences supply chain transparency and resilience. The data indicate that digital twins significantly influence supply chain transparency (β = 0.538, p = 0.001), hence supporting hypothesis H1. The digital twin has a positive and significant influence on supply chain resilience (β = 0.385, p = 0.000); thus, the study adopts hypothesis H2. Additionally, digital twins enhance sustainability performance (β = 0.481, p = 0.003), the study validates hypothesis H3 by examining the impact of supply chain transparency and resilience on sustainability performance (β = 0.452, p = 0.0027) and supply chain resilience (β = 0.237, p=0.000) significantly and positively impact sustainability performance. the study supports hypotheses H4 and H5, indicating that supply chain transparency mediates the relationship between digital twins and sustainability performance. Hypothesis H6 supports this (β = 0.413, p = 0.000), while

hypothesis H7 suggests that supply chain resilience mediates the relationship (β = 0.306, p = 0.000).

The main goal of the study was to look at how the four variables (digital twin, transparency, resilience, and sustainable performance) are related, but the researchers also considered differences between sectors when analyzing the data by checking if the variables were consistent across different sectors. However, an analysis of variance (ANOVA) was not conducted between sectors, which will be considered in future studies to enhance a more profound understanding of the impact of the nature of the industrial sector on the relationship between the studied variables. We recommend conducting in-depth comparative studies across sectors in the future to broaden the scope of the findings.

6. DISCUSSIONS AND CONCLUSIONS

This section delves into the study's findings and their implications. The study examines the influence of digital twins on sustainability performance and highlights the role of supply chain transparency and resilience in enhancing sustainability. Digital twins significantly influence supply chain transparency and supply chain resilience. Additionally, digital twins enhance sustainability performance. We have also assessed the influence of supply chain transparency and resilience on sustainability performance, and they positively influence sustainability performance. in then, supply chain transparency and supply chain resilience mediate the relationship between digital twins and sustainability performance, also that positive effect in the relationship.

Results of the First Hypothesis (H1): The Relationship between Digital Twins and Sustainable Performance:

The results of the statistical analysis indicate a statistically significant positive relationship between the adoption of digital twins and improved sustainable performance in supply chains. The impact coefficient (β = 0.481) and the probability value (p = 0.0031) support the first hypothesis. This result confirms that expanding digital twin applications contributes to enhancing sustainability practices by reducing waste, improving resource efficiency, and increasing flexibility to adapt to environmental and economic changes.

Previous studies have shown results consistent with the findings of the current study. Kamble et al. (2022) demonstrated that the use of digital twins contributes to enhancing environmental and social performance by improving monitoring, control, and forecasting processes in supply chains. Ivanov (2023) also indicated that digital twins enable organizations to improve decision-making and achieve sustainability goals by simulating future scenarios and reducing uncertainty.

In another study, Patil and Pimpale (2024) emphasized the positive role of digital twins in enhancing organizations' sustainable performance by improving transparency, reducing environmental costs, and increasing stakeholder satisfaction. Owida et al. (2022) also demonstrated that digital twins are an effective tool for balancing economic efficiency with environmental and social considerations, contributing to building more sustainable supply chains. Accordingly, the results of the current study are largely consistent with previous literature and support the growing trend toward adopting digital twins as a strategic tool for improving sustainable performance, particularly in resource-intensive industrial sectors that seek to balance profitability with environmental and social responsibility.

Results of the Second Hypothesis: Digital Twins Enhance Supply Chain Transparency

The results indicate a statistically significant positive relationship between digital twins and supply chain transparency (β = 0.538, p = 0.001), indicating that adopting digital twins improves companies' ability to share information and track material and service flows. Several studies support this finding. For example, Ivanov (2023) confirmed that digital twins directly contribute to enhancing transparency by improving real-time visibility of logistics flows within and outside the organization. Kamble, Gunasekaran, Parekh, Mani, Belhadi, and Sharma (2022) also explained that digital twin applications provide accurate digital models that help monitor supply chains with high accuracy, supporting operational transparency and enhancing trust among partners. In light of the above, it is clear that companies that implement digital twin systems are able to improve the transparency of their supply chains, which positively impacts coordination, governance, and sustainable performance.

Results of the Third Hypothesis: Digital Twins Enhance Supply Chain Resilience

The analysis results showed a statistically significant positive relationship between digital twins and supply chain resilience (β = 0.385, p = 0.000). This indicates that the use of digital twins enables companies to predict risks and respond quickly to disruptions in the business environment.

This result is consistent with the study Queiroz et al. (2022) which demonstrated that digital twins are an effective tool for predicting risks and analyzing rapid response scenarios, enhancing companies' resilience in dealing with change. Mittal, Khan, Romero, and Wuest (2023) also stated that digital twins allow for the simulation of crises such as supply disruptions or sudden increases in demand, helping improve real-time decision-making. This demonstrates that

digital twins play a strategic role in supporting supply chain resilience, making them a vital tool in complex business environments.

Results of Hypothesis Four: Supply Chain Transparency Enhances Sustainable Performance

The results revealed a statistically significant positive relationship between supply chain transparency and sustainable performance (β = 0.452, p = 0.0027). This means that increased transparency in the supply chain helps companies achieve their environmental, economic, and social sustainability goals. This result is consistent with Busse et al. (2017) who indicated that supply chain transparency enables companies to monitor the environmental impact of their operations and make more informed sustainability decisions. Linton, Klassen, and Jayaraman (2021) also confirmed that enhanced transparency facilitates companies' improvement of environmental performance, reduction of waste, and promotion of responsible consumption behaviors. Thus, transparency is a pivotal element in enhancing sustainability within industrial supply chains.

Results of Hypothesis Five: Supply Chain Resilience Enhances Sustainable Performance

The results indicated a statistically significant positive relationship between supply chain resilience and sustainable performance (β = 0.237, p = 0.000). This finding confirms that companies' ability to respond and adapt to changes in the business environment contributes to improved long-term sustainable performance. This finding is supported by studies such as Brandon-Jones et al. (2014) and Hosseini et al. (2019), which demonstrated that supply chain resilience reduces operational risks and improves companies' response to environmental and societal crises, enhancing their ability to achieve sustainability goals. Tukamuhabwa et al. (2015) also demonstrated that operational resilience leads to improved environmental efficiency and reduced resource waste.

This demonstrates that supply chain resilience is a key component of achieving sustainable performance in dynamic environments.

Results of Hypothesis 6: Supply chain transparency mediates the relationship between digital twins and sustainable performance

The analysis results revealed a significant mediating effect of supply chain transparency on the relationship between digital twins and sustainable performance (β = 0.413, p = 0.0001). This suggests that one of the pathways through which digital twins impact sustainability is through enhanced transparency. This hypothesis is supported by a study Papetti et al. (2019), which confirmed that digital twins enable accurate and real-time data, contributing to

transparency-based sustainable decision-making. Treiblmaier and Moser (2020) also indicated that transparency is one of the explanatory mechanisms for the impact of new technologies, such as digital twins, on environmental and social outcomes.

Results for Hypothesis 7: Supply chain resilience mediates the relationship between digital twins and sustainable performance

The results showed a significant mediating effect of supply chain resilience between digital twins and sustainable performance ($\beta = 0.306$, $p = 0.000$). This demonstrates that digital twins contribute to enhancing sustainable performance by enabling companies to enhance their resilience.

This finding is consistent with Ivanov and Dolgui (2020) which demonstrated that resilience is an effective way to translate the potential of digital twins into sustainable outcomes, especially in situations of sudden change or crisis. Wamba et al. (2022) also demonstrated that digital technologies enable organizations to prepare and react efficiently, which positively impacts all three dimensions of sustainability.

Digital twins are crucial for improving the resilience, performance, and supply chain sustainability. They boost customer satisfaction, product quality, and waste reduction. They also improve supply chain transparency, transparency, and traceability. They foster supply chain partnerships, optimize inventory strategies, and propose alternative supply sources. Digital twins also reduce costs, increase return on investment, and improve stakeholder perception. The study examines digital twins through the lens of sustainable performance.

6.1 Implication of the Study

The managerial implication of this study is that it presents a framework for comprehending sustainable performance and enhancing knowledge. It proposes the development of digital twins to meet requirements for transparency, resilience, and sustainability. Establishing the parameters and measuring the interactions among these concepts is essential for effective management (Owida et al., 2022). Digital twins facilitate comprehension of the dynamics and interdependencies of sustainability performance, optimizing productivity, efficiency, and cost advantages (Ivanov, 2023).

Digital twins allow stakeholders to model various situations and evaluate their effects on resilience and transparency, facilitating adaptable decision-making. They provide real-time oversight of manufacturing and supply chain activities, minimizing disruptions and deploying resilience strategies such as real-time inventory management. Digital twins facilitate predictive maintenance strategies,

minimizing downtime and enhancing operational reliability. Digital twins enable data interchange and informed decision-making, promoting efficient communication and collaboration among stakeholders. This leads to more resilient and durable supply chains in manufacturing.

the importance of using the term "supply chain transparency" carefully in future studies on sustainability. It suggests that a framework should be developed to guide future research on supply chain transparency and sustainable performance. The study also highlights the need for more information on internal procedures in businesses regarding supply chain transparency. It also highlights the relationship between sustainability and supply chain resilience, emphasizing the need to tackle these goals simultaneously. The study presents a conceptual framework to explain the multidimensional nature of the relationship between SC resilience and sustainability performance.

6.2 Limitations and Future Research Directions

The study's scope is limited to Egypt, a region experiencing significant global transformation. The literature requires constant revitalization to stay current with changing contexts. Future research should explore the feasibility of conducting the study in other developing nations. The study could also incorporate new factors like blockchain, AI, and IOT for more intricate interconnections. A more extensive sample by industry could be collected to analyze the correlations between digital twins and sustainable performance techniques and their association with fundamental obstacles. This is a critical domain for future research efforts.

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Appendix A

Please rate the following on a scale of 1–5, where 1 is strongly agree, and 5 is strongly disagree

Construct and items.   References

Digital twin (DT)

1-DT enables the direct monitoring of products and services and increases visibility.

2-DT enhances the coordination among the SC partners.

3-DT provides real-time monitoring of the process and product, reducing disruption and breakdowns.

4-DT increases the transparency in SC.   (Kamble et al., 2022;

5-DT enables the SC to react quickly to supply and demand.   Singh & Singh, 2023)

6-DT reduces the lead time in the SC.

7-DT provides data that can help predict the risks.

8-DT enhances the quality of information, which improves better decision-making.

9-DT gathers data from various sources for better forecasting.

Supply chain transparency

10-SCT believe that SCT My organization perceives that Supply chain transparency (SCT) is essential for enhancing accountability and ethical practices

11-My organization perceives that the current efforts and mechanisms in place provide visibility into the various stages and processes   (Dolgui & Ivanov,
                                                                                          2020; Wu & Yu,
12-My organization perceives that improved SCT can lead to better risk management, stakeholder   2023; Xu et al., 2021)
trust, and responsiveness

13-My organization perceives that SCT contributes to a positive brand image and fosters sustainable practices

Supply chain resilience (SCR)

14-DT enhances the supply chain alertness.

15-The DT increases the capability of an organization to recuperate from supply chain   (Mubarik et al., 2021;
disturbances.   Qader et al., 2022).

16-DT improves the supply chain's preparedness for unexpected changes.

Sustainable performance

17-My organization perceives that achieving sustainable organizational performance is crucial for ensuring long-term success and positive impact in our SC.

18-My organization perceives that current sustainability practices and initiatives implemented enhance resource efficiency, minimize environmental impact, and promote responsible   (Wang et al., 2018;
practices.   Zaid et al., 2018).

19-My organization perceives that sustainable organizational performance leads to improved competitiveness, stakeholder engagement, and resilience in SC.

20-My organization perceives that sustainable organizational performance aligns with its values and contributes to positive social and environmental outcomes within SC.

الدور الوسيط لشفافية ومرونة سلاسل الإمداد في العلاقة بين التوائم الرقمية والأداء المستدام (بالتطبيق على قطاع الصناعات المصرية)

د. محمد جميل محمد

ملخص البحث باللغة العربية

تتناول هذه الدراسة أثر التوائم الرقمية (Digital Twins) على إستدامة سلاسل الإمداد، مع التركيز على كل من الشفافية والمرونة. تُعد التوائم الرقمية تمثيلات افتراضية في الوقت الفعلي للعمليات ، وتسهم في تعزيز كفاءة الاستدامة في سلاسل الإمداد من خلال تحسين التنسيق، والرؤية الشاملة، والقدرة على التكيف، ودقة التنبؤ. ويؤدي دمج التوائم الرقمية مع تقنيات الذكاء الاصطناعي ومفاهيم الشفافية والمرونة إلى تمكين المراقبة في الوقت الفعلي ، وتحسين استخدام الموارد، والحد من آثار الاضطرابات. تم استخدام نموذج المعادلات الهيكلية (SEM) لدراسة العلاقات بين التوائم الرقمية، وشفافية سلسلة الإمداد (SCT)، ومرونة سلسلة الإمداد (SCR)، والأداء المستدام في قطاع التصنيع المصري. وقد تم جمع البيانات الأولية من خلال استبيانات على عينة مكوّنة من 248 مديرًا في شركات صناعية متنوعة داخل مصر.

أظهرت النتائج أن التوائم الرقمية تُسهم بشكل ملحوظ في تعزيز كل من الشفافية والمرونة في سلاسل الإمداد، مما ينعكس إيجابيًا على الأداء المستدام. كما تبين أن كلًا من الشفافية والمرونة تلعبان دور الوسيط في العلاقة بين التوائم الرقمية والأداء المستدام، مما يعزز من أهميتهما في تحقيق الاستقرار طويل الأمد لسلاسل الإمداد. تقدم هذه الدراسة إطارًا مفاهيميًا ورؤئً تجريبية حول تبنّي التكنولوجيا الرقمية لتحقيق استدامة العمليات الصناعية. وتوصي الدراسة بمزيد من الأبحاث المستقبلية لتوسيع نطاق تطبيق التوائم الرقمية في قطاعات صناعية متنوعة، مع دمج التقنيات الناشئة مثل سلسلة الكتل (البلوك تشين) والذكاء الاصطناعي لتعزيز كفاءة واستدامة سلاسل الإمداد.

الكلمات الدالة : التوائم الرقمية، الأداء المستدام، شفافية سلسلة الإمداد، مرونة سلسلة الإمداد.

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