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Determinants of digital twin adoption readiness in logistics: Evidence from Egypt's emerging logistics sector

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Authors:
Islam El-Nakib[1]
Sara Elzarka[1]

Affiliations:
[1]College of Business, Effat University, Jeddah, Saudi Arabia

Corresponding author:
Islam El-Nakib,
iselnakib@effatuniversity.edu.sa

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Background: Digital twin technology can improve operational visibility, system monitoring and decision support in logistics. However, empirical evidence on organisational readiness for adoption remains limited in emerging logistics economies.

Objectives: This study examines organisational readiness for digital twin adoption in Egypt's logistics sector by assessing the effects of perceived operational benefits, digital workforce skills, managerial support and investment uncertainty.

Method: A cross-sectional survey was conducted with 500 logistics professionals across major logistics hubs in Egypt. The questionnaire measured perceived digital twin benefits, workforce digital capabilities, managerial commitment and financial uncertainty. Multiple regression analysis was used to test the determinants of adoption readiness.

Results: Perceived operational benefits, digital workforce skills and managerial support had significant positive effects on adoption readiness. Investment uncertainty had a significant negative effect, showing that financial concerns remain an important implementation barrier.

Conclusion: Digital twin adoption readiness in logistics depends less on technological feasibility alone and more on organisational capability, managerial commitment and investment clarity.

Contribution: The study provides Egypt-specific evidence on the readiness conditions shaping digital twin adoption before full implementation. It offers practical guidance for logistics firms and policymakers seeking to move from digital twin awareness to adoption readiness.

Keywords: digital twin; logistics; technology readiness; digital transformation; supply chain resilience; Egypt.

Introduction

Egypt's logistics sector has strategic importance because it connects regional and global trade flows through the Suez Canal, Mediterranean ports, Red Sea links and inland logistics corridors. Recent investments in port modernisation, logistics zones and the Suez Canal Economic Zone have increased the need for better operational visibility and data-based decision-making. As freight flows become more complex, logistics firms need digital tools that can support monitoring, scenario testing and coordination across transport, warehousing and port operations (Le & Fan 2024). Regional supply chain research shows that digital transformation, resilience and sustainability have become central priorities in MENA logistics systems, while organisational capability remains essential for their effective implementation (El-Nakib & Elzarka 2026). In addition, literature and national logistics policy documents highlight the growing relevance of digital twins, smart infrastructure and AI-enabled supply chain coordination for logistics performance and resilience (Abdillah & Wahyuilahi 2024; Alguirat, Lehyani & Zouari 2025; Alnaser, Maxi & Elmousalami 2024; Cimino et al. 2024; Galkin et al. 2025; Liu, Pan & Ballot 2024; Ministry of Transport 2024).

Digital twins are increasingly discussed as tools for improving logistics planning and operational control. In this study, a digital twin is understood as a data-linked model that helps logistics firms monitor operations, test scenarios, and support decisions before changes are made in physical systems (Jones et al. 2020; Tao et al. 2018).

In logistics, digital twins can support route optimisation, predictive maintenance, inventory visibility, warehouse simulation and supply chain monitoring (Bandara & Buics 2024;

Roman et al. 2025). Yet prior research still focuses more on technical architecture and conceptual design than on organisational readiness for adoption in logistics firms (Ivanov 2023).

This study addresses this gap by examining digital twin adoption readiness in Egypt's logistics sector. The focus is not on whether digital twins can improve logistics performance after implementation, but on whether firms have the readiness conditions needed before implementation. This distinction is important because many logistics firms may recognise the value of digital twins while still facing capability, managerial or investment barriers that delay adoption (Benhamou, Giard & Lamouri 2026).

This study contributes to logistics digitalisation research in three ways. Firstly, it provides Egypt-specific empirical evidence on digital twin adoption readiness across major logistics hubs. Secondly, it explains readiness through four organisational determinants: perceived operational benefits, digital workforce skills, managerial support and investment uncertainty. Thirdly, it positions digital twin adoption as an early-stage readiness issue rather than an implementation maturity or performance outcome issue. This distinction separates the present study from research that examines post-adoption performance consequences (Hossain et al. 2025; Ogunsoto, Olivares-Aguila & ElMaraghy 2025).

The remainder of this article is structured as follows. 'Literature review' section reviews the literature on digital twin technology in logistics and identifies the research gap. `Research methods and design' section presents the research methodology and survey design. `Results' section reports the empirical results. 'Discussion' section discusses the findings and their implications. 'Conclusion' section concludes the study and outlines directions for future research.

Literature review

Digital twin technology in logistics: A conceptual scope

A digital twin is commonly defined as a digital representation of a physical asset, process or system that is updated through data exchange with its physical counterpart (Grieves & Vickers 2017; Jones et al. 2020; Tao et al. 2018). In logistics, this concept is useful because transport, warehousing and port operations depend on continuous flows of data, assets and decisions. Digital twins can help firms monitor operating conditions, simulate alternatives and improve decision-making under uncertainty. Rather than treating digital twins only as technical models, this study views them as organisational decision-support tools whose value depends on the firm's ability to use data, skills and managerial support effectively. This readiness perspective is important for emerging logistics contexts where infrastructure investment may advance faster than organisational digital capability (Agnusdei, Elia & Gnoni 2021; Bandara & Buics 2024; Jones et al. 2020; Ogunsoto et al. 2025; Roman et al. 2025).

Reported benefits in logistics literature

The logistics literature identifies several operational benefits of digital twins. Route optimisation is one common application because twin-enabled models can combine data on traffic, assets, demand and delivery conditions to support better routing decisions (Bandara & Buics 2024; Roman et al. 2025). Predictive maintenance is another important use because digital twins can monitor asset condition and support early detection of failure risks, which may reduce downtime and improve asset availability (Attaran & Celik 2023). In warehousing and inventory management, digital twins can support layout testing, inventory visibility and capacity planning. These benefits matter in Egypt's logistics sector because port, corridor and warehouse operations increasingly require faster coordination across multiple actors and locations (Samuels 2025).

While the operational benefits of digital twin technology are increasingly documented, existing studies primarily emphasise technological capabilities rather than organisational readiness. Recent research highlights that successful digital transformation in logistics depends not only on technology availability but also on workforce capabilities, managerial support and organisational digital maturity (Bandara & Buics 2024). However, empirical studies examining these readiness conditions within logistics organisations remain limited. This study, therefore, focuses on the organisational dimension of digital twin technology adoption by examining awareness levels, perceived benefits and readiness barriers among logistics professionals (Benhamou et al. 2026).

Recent studies also link digital twins to lean supply chain management, resilience analysis, hierarchical modelling and construction-sector applications (Guo & Mantravadi 2025; Ivanov 2025; Jarzyńska, Nierychlok & Olender-Skóra 2026; Nakache, Féniès & Ren 2025; Singh et al. 2024; Su, Zhong & Jiang 2025).

Adoption barriers

Despite the reported advantages, the adoption of digital twin technology in logistics is hindered by multiple long-lasting barriers. The literature suggests that many of these barriers are linked to organisational readiness rather than technological feasibility. For example, skill shortages are often identified as a barrier. According to Alnaser and Elmousalami (2025), capabilities in data analytics, IoT integration, systems modelling and digital operations management are required for effective digital twin technology deployment. Logistics organisations often lack such skills. Without these skills, an organisation cannot develop digital twin technology and interpret its output to act on it (Samuels 2025).

As a result, firms may depend heavily on external vendors, which can increase cost, data governance concerns and loss of internal implementation capability. The uncertainty of return on investment (ROI) creates another hurdle. This barrier is especially relevant in capital-intensive logistics operations with narrow margins.

Implementation often requires upfront investment in sensors, data infrastructure, software platforms and training.

As noted in several papers, organisations frequently struggle to quantify expected financial returns (Attaran & Celik 2023). This is particularly true when the benefits are indirect, concern resilience or visibility or are long-term. The uncertainty slows decision-making and limits many digital twin technology initiatives to pilot implementation rather than full-scale rollout. Management support and organisational commitment also affect readiness barriers. Weak senior management support may leave digital twin initiatives without strategic alignment, cross-functional coordination or sustained funding (Bandara & Buics 2024). In logistics organisations with siloed structures, resistance to change and competing operational priorities often act as inhibitors of adoption. Other inhibitors relate to data security, interoperability with legacy systems and digital maturity (Alquraish 2025). Related research in Egypt and other fossil-fuel-dependent logistics systems likewise identifies human-centred, internal and external organisational barriers to sustainability-oriented supply-chain transformation (El-Nakib, Elzarka & Gouhar 2026; Elzarka, Gouhar & El-Nakib 2026).

This study uses the Technology Acceptance Model (TAM) and organisational readiness logic to explain digital twin adoption readiness. Perceived operational benefits reflect TAM's perceived usefulness logic because firms are more likely to support adoption when they expect clear operational value (Davis 1989). Digital workforce skills and managerial support reflect internal readiness conditions because adoption requires employee capability, leadership commitment and resource support. Investment uncertainty reflects perceived implementation risk, as firms may delay adoption when costs are high and returns are unclear. The Technology–Organisation–Environment (TOE) framework is used as a supporting perspective because it helps explain how technological value, organisational capability and contextual constraints jointly shape adoption decisions (Tornatzky & Fleischer 1990).

Research gap

Digital twin applications have been studied in manufacturing, construction, smart infrastructure and supply chain modelling, but empirical evidence on adoption readiness in logistics remains limited. In Egypt, existing digital twin studies focus mainly on construction, smart cities and infrastructure applications rather than logistics operations (Alnaser & Elmousalami 2025). This creates a gap in understanding how logistics professionals perceive digital twins and which readiness conditions shape adoption. The unresolved issue is not only whether digital twins can support logistics operations, but whether firms have the skills, managerial support and investment clarity needed to adopt them. This study addresses that gap through evidence from Egypt's logistics sector.

Research questions

The study addresses this gap through four research questions:

- **RQ1:** What is the level of awareness of digital twin technology among logistics professionals in Egypt?
- **RQ2:** What operational benefits do logistics professionals associate with digital twin technology adoption?
- **RQ3:** What organisational barriers limit digital twin technology implementation within logistics firms?
- **RQ4:** What level of organisational readiness exists for digital twin technology adoption in Egypt's logistics sector?

Conceptual framework and hypotheses

Figure 1 presents the conceptual framework used in this study. The model examines the organisational determinants of digital twin adoption readiness within logistics firms. Drawing on the literature on digital transformation and technology adoption, the framework proposes that perceived operational benefits, digital workforce skills and managerial support positively influence organisational readiness for digital twin adoption. In contrast, investment uncertainty is expected to negatively affect adoption readiness. These relationships reflect the organisational capabilities and perceived value considerations that shape technology adoption decisions in logistics environments. The proposed relationships are examined empirically using regression analysis. This adoption logic is also consistent with user acceptance research, which emphasises perceived usefulness, support conditions and facilitating factors in technology adoption decisions (Venkatesh et al. 2003).

The hypotheses are developed by linking the study constructs to TAM, organisational readiness logic and TOE.

From a TAM perspective, perceived usefulness increases support for technology adoption. In the present study, perceived usefulness is reflected in the expected operational benefits of digital twins, including route optimisation, predictive maintenance, inventory visibility and warehouse simulation:

> **H1:** Perceived operational benefits positively influence digital twin adoption readiness.

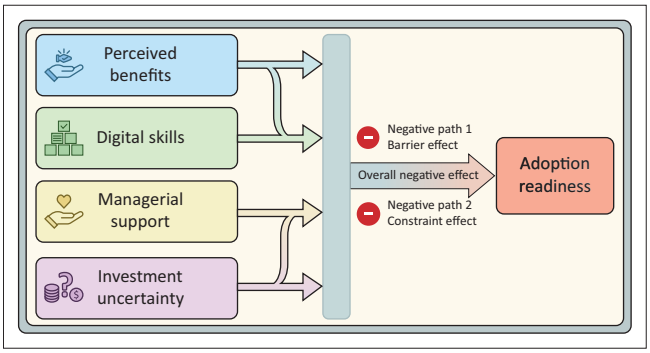


FIGURE 1: Conceptual framework of digital twin adoption readiness in logistics.

Digital twin adoption also depends on internal organisational readiness. Logistics firms need employees who can use data, IoT systems and simulation outputs in operational decisions. Workforce digital skills, therefore, represent a core capability for moving from awareness to adoption readiness:

> **H2:** Workforce digital skills positively influence digital twin adoption readiness.

Managerial support is another important readiness condition. Senior managers provide strategic direction, resource allocation, and cross-functional coordination for technology adoption. Without such support, digital twin initiatives may remain fragmented or limited to early experimentation:

> **H3:** Managerial support positively influences digital twin adoption readiness.

Investment uncertainty reflects perceived implementation risk within the TOE logic. Digital twin adoption often requires investment in sensors, data infrastructure, software platforms and training. When expected returns are unclear, firms may delay adoption decisions:

> **H4:** Investment uncertainty negatively influences digital twin adoption readiness.

Together, these hypotheses position digital twin adoption readiness as a function of perceived operational usefulness, internal organisational capability, managerial commitment and perceived investment risk.

Research methods and design

This study used a cross-sectional survey design to examine organisational readiness for digital twin adoption in Egypt's logistics sector (Creswell & Creswell 2018; Saunders, Lewis & Thornhill 2019). The analysis followed six steps: descriptive statistics, reliability testing, exploratory factor analysis, correlation analysis, multiple regression and hierarchical robustness checks.

Population and sampling

The study population consisted of logistics professionals working in freight forwarding, port operations, warehousing and last-mile delivery within Egypt. Respondents were recruited from major logistics hubs, including Alexandria, Cairo logistics clusters, Port Said and the Suez Canal Economic Zone. These locations represent the primary centres of freight movement and logistics operations in Egypt. Logistics activities vary across subsectors such as freight forwarding, port operations, warehousing and last-mile delivery. Digital twin technology applications can support logistics coordination across major freight corridors connecting Alexandria, Cairo and Port Said. The sampling method used was convenience sampling with purposive elements. This approach was selected because a comprehensive national database of logistics professionals is not available in Egypt. The researchers aimed to capture diversity across subsectors, organisation sizes and professional roles.

The survey was distributed to logistics professionals working in logistics firms, freight forwarding companies, and supply chain service providers across Egypt. A total of 500 valid responses were collected and used for analysis. The data used in this study were collected independently for the Egyptian logistics sector and are distinct from other regional digital twin adoption datasets. Respondents included logistics managers, supply chain specialists, operations managers and technology specialists involved in logistics digitalisation initiatives.

The sampling process aimed to improve coverage across logistics subsectors and organisational roles, while recognising that the sample is not statistically representative of the entire Egyptian logistics workforce.

Respondents were recruited through professional logistics networks, LinkedIn industry groups, logistics companies and academic-industry partnerships. Participation required respondents to have at least 1 year of professional experience in logistics operations. Although convenience sampling was used because of the absence of a comprehensive industry database, efforts were made to ensure diversity across subsectors, job roles and organisation sizes. A total of 500 valid responses were collected from logistics professionals across Egypt's major logistics hubs. The sample size is adequate for descriptive analysis and subgroup comparisons. A sample size of 500 respondents exceeds the minimum threshold recommended for regression analysis and exploratory factor analysis in organisational research.

Data collection

Data were collected electronically using a self-administered web-based questionnaire built on Google Forms and Qualtrics for easy access and data security. The questionnaire items were developed based on constructs identified in previous studies on digital transformation and digital twin technology adoption. To ensure content validity, the survey instrument was reviewed by three academic experts in logistics and two industry practitioners. A pilot test involving 20 logistics professionals was conducted to evaluate clarity and reliability. Minor wording adjustments were made based on pilot feedback. The survey questionnaire was divided into four broad sections:

- **Demographics:** Age, gender, education, years of experience, job role, sub-sector, organisation size and hub location (multiple-choice and categorical items) as summarised in Table 1.
- **Familiarity with digital twin technology:** A single multiple-choice item measured level of understanding, with options including no knowledge, basic awareness, moderate understanding and advanced expertise. A multi-select item captured sources of knowledge.
- **Perceived benefits and challenges:** Five-point Likert-scale items were used to measure perceived benefits and challenges, using a scale from 1 = strongly disagree to 5 = strongly agree. Benefit items covered route optimisation,

TABLE 1: Demographic characteristics of survey respondents (N = 500).

Variable	Category	*n*	%
Gender	Male	370	74
	Female	120	24
	Other	10	2
Age (years)	18–34	160	32
	35–44	180	36
	45–54	110	22
	≥ 55	50	10
Education level	High school or Diploma	60	12
	Bachelor's degree	280	56
	Master's or PhD	140	28
	Other	20	4
Years of experience	0–5	120	24
	6–10	150	30
	11–15	120	24
	≥ 16	110	22
Job role	Manager or Supervisor	170	34
	Analyst or Specialist	190	38
	Operations coordinator	140	28
Sub-sector	Freight forwarding	120	24
	Port operations	130	26
	Warehousing	110	22
	Last-mile delivery	140	28
Organisation size	Small (< 50 employees)	130	26
	Medium (50–250)	180	36
	Large (> 250)	190	38
Hub location	Alexandria	150	30
	Cairo	170	34
	Port Said	90	18
	Suez Canal Economic Zone	90	18

PhD, Doctor of Philosophy.

predictive maintenance, real-time inventory tracking, warehouse layout simulation and supply chain visibility. Challenge items covered digital skills gaps, uncertainty regarding ROI, implementation cost, data security concerns, interoperability with legacy systems and limited organisational digital maturity. Items were adapted from prior digital twin and Industry 4.0 logistics literature (Bandara & Buics 2024; Roman et al. 2025).

- **Implementation status and training preferences:** Multiple choices on current implementation status (e.g. none, pilot, full-scale).

A total of 500 valid responses were retained after screening for completeness and relevance to logistics-sector experience. Because the survey was distributed through professional networks, LinkedIn groups, logistics firms and academic–industry contacts, the total number of individuals who viewed the invitation could not be verified.

A precise response rate, therefore, could not be calculated. The first page of the questionnaire explained the study purpose, voluntary participation, anonymity, confidentiality and the right to withdraw. Respondents provided informed consent electronically before completing the questionnaire.

Table 1 presents the demographic characteristics of the survey respondents. A total of 500 valid responses were collected from logistics professionals working across Egypt's major logistics hubs. The majority of respondents were male (74%), reflecting the gender distribution commonly observed in the logistics and transport sector.

Female respondents represented 24% of the sample, while 2% identified as other. The largest age group was 35–44 years (36%), followed by respondents aged 18–34 years (32%), indicating that most participants were mid-career professionals involved in logistics operations and supply chain management. In terms of education, the majority of respondents held a bachelor's degree (56%), while 28% reported a master's or doctoral degree.

Regarding professional experience, the largest group had between 6 and 10 years of experience (30%), followed by 11–15 years (24%). Respondents represented a variety of organisational roles, including managers or supervisors (34%), analysts or specialists (38%) and operational coordinators (28%). The sample also reflects diverse logistics subsectors, including freight forwarding (24%), port operations (26%), warehousing (22%) and last-mile delivery (28%). Most respondents worked in medium-to-large logistics organisations, with 38% employed in large firms and 36% in medium-sized companies. Geographically, respondents were distributed across Egypt's primary logistics hubs, including Alexandria (30%), Cairo (34%), Port Said (18%) and the Suez Canal Economic Zone (18%).

Measurement model

The study used multi-item constructs to measure the determinants of digital twin adoption. All items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Perceived benefits were measured using four items reflecting operational improvements enabled by digital twins, including route optimisation, predictive maintenance, inventory visibility and warehouse simulation. Digital skills were measured using three items capturing the technological capabilities of employees, including data analytics capability, IoT integration knowledge and simulation modelling ability. Managerial support was measured using three items reflecting leadership commitment to digital transformation, digital strategy support and funding availability. Investment uncertainty was measured using three items capturing perceived financial risks, including ROI ambiguity, cost concerns and investment risk. Adoption readiness was measured using three items reflecting the organisation's readiness to implement digital twin technology in logistics operations.

The measurement items were adapted from prior research on digital transformation, technology adoption and Industry 4.0 implementation in logistics and supply chain management (Bandara & Buics 2024; Roman et al. 2025).

Measurement reliability and validity assessment

The internal consistency of the measurement constructs was evaluated using Cronbach's alpha. All constructs

exceeded the recommended threshold of 0.70, indicating acceptable reliability. Table 2 presents the measurement reliability.

Exploratory factor analysis was conducted to examine the validity of the measurement model. The Kaiser–Meyer-Olkin (KMO) value exceeded the recommended threshold of 0.70, indicating sampling adequacy. Bartlett's test of sphericity was significant $p < 0.001$, confirming the suitability of the data for factor analysis. All factor loadings exceeded 0.60, indicating satisfactory convergent validity. Table 3 summarises the validity assessment.

Data analysis and limitations

Data were analysed using SPSS. Frequencies, percentages, means and standard deviations (SD) were used to describe awareness, perceived benefits, challenges, implementation status and training preferences. Reliability was assessed using Cronbach's alpha. Exploratory factor analysis was used to assess construct validity. Pearson correlations were used to examine associations among the main constructs. Multiple regression was then applied to test the determinants of digital twin adoption readiness.

To examine the determinants of digital twin technology adoption readiness, multiple regression analysis was applied. The regression model included perceived benefits, digital workforce skills, managerial support and investment uncertainty as independent variables, while adoption readiness was treated as the dependent variable.

The detailed regression results are presented in the 'Results' section. Several limitations should be acknowledged.

Firstly, the study relies on self-reported perceptions, which may be affected by social desirability or recall bias.

Respondents may overstate their awareness of digital twins or their organisation's readiness. Secondly, convenience sampling limits generalisability. The sample may overrepresent digitally engaged professionals and firms connected to professional networks. Smaller firms and organisations with lower digital maturity may be underrepresented. Thirdly, the cross-sectional design captures perceptions at one point in time and does not allow causal claims or analysis of readiness changes over time. Future research could use longitudinal designs, probability-based sampling and comparative country studies.

TABLE 2: Reliability analysis of measurement constructs.

Construct	Items	Cronbach α
Perceived benefits	4	0.88
Digital skills	3	0.84
Managerial support	3	0.86
Investment uncertainty	3	0.79
Adoption readiness	3	0.90

TABLE 3: Validity assessment.

Construct	Item	Loading
Perceived benefits	Route optimisation	0.82
	Predictive maintenance	0.85
	Inventory visibility	0.79
	Warehouse simulation	0.83
Digital skills	Data analytics capability	0.81
	IoT integration knowledge	0.77
	Simulation modelling ability	0.80

Before presenting the regression results, two additional diagnostics were examined to ensure the robustness of the statistical model. Firstly, model summary statistics were assessed to evaluate the overall explanatory power of the regression model. The model explains a substantial proportion of the variance in digital twin adoption readiness, with an R^2 value of 0.54 and an adjusted R^2 of approximately 0.53. The overall model is statistically significant, as indicated by an F-statistic of approximately 85 with a significance level of $p < 0.001$. These results indicate that the independent variables collectively provide a strong explanation of organisational readiness for digital twin adoption. Secondly, multicollinearity among the independent variables was examined using the variance inflation factor (VIF) values. Multicollinearity diagnostics indicate that all VIF values are well below the commonly accepted threshold of 5, suggesting that multicollinearity does not pose a concern in the regression model. The VIF values are 2.1 for perceived benefits, 1.9 for digital skills, 2.3 for managerial support and 1.7 for investment uncertainty. These values confirm that the independent variables are sufficiently distinct and suitable for inclusion in the regression analysis.

Ethical considerations

This article followed all ethical standards for research and received an ethical clearance waiver from the College of Business, Effat University. The study involved an anonymous online survey of logistics professionals. Participants were informed about the study purpose, voluntary participation, confidentiality and the right to withdraw, and electronic informed consent was obtained before completing the questionnaire. No personally identifiable information was collected or reported.

Results

This section presents the empirical findings based on 500 valid responses from logistics professionals working across Egypt's major logistics hubs. The analysis examines awareness of digital twin technology, perceived operational benefits, perceived implementation challenges and organisational readiness for adoption. It also reports the statistical relationships among the main study constructs and identifies the key determinants of digital twin adoption readiness.

Descriptive statistics and correlation analysis

Table 4 shows generally positive perceptions toward digital twin adoption. Perceived benefits recorded the highest mean,

followed by managerial support and digital workforce skills. Investment uncertainty recorded the lowest mean, indicating that financial risk remains a concern. Adoption readiness was moderate to high, suggesting interest in digital twin adoption but not full implementation readiness.

To further examine relationships between the constructs, correlation analysis was conducted. Table 5 presents the correlation matrix for the main variables included in the study. The results show a strong positive relationship between perceived benefits and adoption readiness ($r = 0.57$), suggesting that organisations that recognise the operational advantages of digital twin technology are more likely to adopt it. Digital workforce skills also demonstrate a positive relationship with adoption readiness ($r = 0.49$). This finding suggests that organisations with stronger digital capabilities are better positioned to implement advanced technologies such as digital twins.

Managerial support is also positively correlated with adoption readiness ($r = 0.46$), indicating that leadership commitment plays an important role in facilitating technology adoption. Investment uncertainty shows a negative correlation with adoption readiness ($r = –0.34$). This suggests that financial risk perceptions may discourage organisations from investing in digital twin technology.

The correlation results provide preliminary evidence of relationships among the key constructs. However, correlation analysis alone does not establish causal relationships. Therefore, regression analysis was conducted to examine the determinants of digital twin adoption readiness.

Awareness of digital twin technology

The survey examined respondents' awareness of digital twin technology within the logistics sector. Awareness is a critical factor influencing the adoption of emerging technologies, as organisations must first understand the potential applications and benefits of new digital tools before implementing them. The results indicate moderate levels of awareness among logistics professionals. Approximately 18% of respondents reported having no knowledge of digital twin technology, while 36% reported only basic awareness of the concept.

A further 28% of respondents indicated a moderate understanding, suggesting familiarity with the concept and potential applications of digital twin technology in logistics operations. More advanced knowledge levels were reported by a smaller proportion of respondents. Fourteen per cent reported advanced understanding, while 4% identified themselves as experts in digital twin technology.

The findings show that while awareness of digital twin technology is growing within the logistics sector, many professionals still have limited knowledge of the technology's capabilities. Awareness levels vary across logistics subsectors. Professionals working in port operations reported the highest awareness levels, with 62% indicating moderate or higher understanding. This finding likely reflects the increasing use of digital technologies in modern port operations, including automated cargo handling systems and real-time monitoring technologies.

Respondents working in warehousing operations reported moderate awareness levels, with 54% indicating moderate or higher knowledge. This may reflect the growing adoption of warehouse automation and inventory tracking systems. Awareness levels were slightly lower among freight forwarding professionals, where 47.8% reported moderate or higher awareness. The lowest awareness levels were observed among professionals working in last-mile delivery operations, where only 41.3% reported moderate or higher knowledge. This may reflect the fact that last-mile logistics operations often prioritise mobile applications and route optimisation technologies rather than complex simulation systems such as digital twins. Awareness also varies by organisational role.

Managers and supervisors demonstrate the highest awareness levels, with 64% reporting moderate or higher knowledge of digital twin technology. This finding suggests that decision-makers are more likely to be exposed to emerging technology discussions and industry developments. Analysts and specialists report moderate awareness levels (51%), while operational staff report the lowest awareness levels (32.5%).

TABLE 4: Descriptive statistics of study constructs ($N = 500$).

Variable	Mean	SD
1. Perceived benefits	4.12	0.71
2. Digital skills	3.88	0.75
3. Managerial support	3.94	0.69
4. Investment uncertainty	3.21	0.82
5. Adoption readiness	3.97	0.73

Note: Values below the diagonal represent Pearson correlation coefficients.
SD, standard deviation.

TABLE 5: Correlation matrix of study variables.

Variable	Mean	SD	1	2	3	4	5
1. Perceived benefits	4.12	0.71	1	-	-	-	-
2. Digital skills	3.88	0.75	0.45***	1	-	-	-
3. Managerial support	3.94	0.69	0.41***	0.48***	1	-	-
4. Investment uncertainty	3.21	0.82	-0.28***	-0.21**	-0.25**	1	-
5. Adoption readiness	3.97	0.73	0.57***	0.49***	0.46***	-0.34***	1

SD, standard deviation.
**, $p < 0.01$; ***, $p < 0.001$.

Organisational size also influences awareness levels. Respondents working in large organisations with more than 250 employees show the highest awareness levels (61.2%), while those working in medium-sized organisations report moderate awareness levels (48.3%). Small organisations demonstrate the lowest awareness levels (38.3%).

Experience also appears to influence awareness levels. Professionals with more than 16 years of experience show the highest awareness levels (60%), suggesting that experienced professionals are more likely to be exposed to technological developments through industry networks and professional conferences. Geographic location also influences awareness levels. Respondents working in the Suez Canal Economic Zone report the highest awareness levels (62.5%), followed by Cairo (59.2%), Alexandria (54.5%) and Port Said (48.6%). Overall, these findings indicate that awareness of digital twin technology varies across logistics subsectors, organisational roles and geographic locations.

Perceived benefits and challenges

The study also examined respondents' perceptions of the main benefits and challenges linked to digital twin technology adoption. The descriptive results indicate strong agreement on the operational value of digital twin technology in logistics. Route optimisation was rated as the highest perceived benefit, with a mean score of 4.31 (SD = 0.68). This result suggests that respondents view digital twins as useful tools for improving logistics routing decisions and reducing operational inefficiencies.

Predictive maintenance also received strong support (M = 4.28, SD = 0.71). This indicates that logistics professionals believe digital twin systems can improve maintenance planning, reduce unexpected equipment failures and support better asset utilisation. Real-time inventory tracking was also highly rated (M = 4.19, SD = 0.74), reflecting the importance of inventory visibility in logistics operations. Warehouse layout simulation received a mean score of 4.14 (SD = 0.79), showing that respondents recognise the value of digital twins in warehouse design, capacity planning and operational flow analysis. Benefits related to supply chain visibility and resilience also received a positive rating (M = 4.12, SD = 0.82), suggesting that digital twins can support better coordination across logistics networks.

Despite these perceived benefits, respondents identified several barriers that may limit adoption. The most significant challenge was the lack of digital skills related to data analytics and IoT technologies (M = 4.36, SD = 0.69). This finding indicates that skills gaps remain a major constraint for logistics firms seeking to implement digital twin systems. Uncertainty regarding ROI was the second strongest barrier (M = 4.27, SD = 0.73), suggesting that financial concerns may slow adoption decisions, particularly when the expected benefits are difficult to quantify in the short term.

Other reported challenges include limited managerial support, high implementation costs, data security concerns, interoperability problems with legacy systems and limited organisational digital maturity. Overall, the findings show that logistics professionals recognise the operational value of digital twin technology, but adoption remains constrained by workforce capability gaps, financial uncertainty and organisational readiness barriers.

Regression analysis

To examine the determinants of digital twin technology adoption readiness, multiple regression analysis was conducted. The regression model included perceived benefits, digital workforce skills, managerial support and investment uncertainty as independent variables, while adoption readiness was treated as the dependent variable.

Prior to conducting regression analysis, multicollinearity diagnostics were examined using VIF values. All VIF values were below the recommended threshold of 5, indicating that multicollinearity does not pose a significant concern. The regression model explains a substantial proportion of the variance in adoption readiness. The model produces an R^2 value of 0.54, indicating that approximately 54% of the variation in adoption readiness can be explained by the independent variables included in the model. The overall regression model is statistically significant ($F = 85$, $p < 0.001$), indicating that the independent variables collectively provide a strong explanation of adoption readiness. Table 6 summarises the regression results.

The results show that perceived benefits have the strongest positive effect on adoption readiness ($\beta = 0.42$, $p < 0.001$). This finding suggests that organisations that recognise the operational advantages of digital twin technology are significantly more likely to adopt the technology. Digital workforce skills also have a strong positive influence on adoption readiness ($\beta = 0.33$, $p < 0.001$), highlighting the importance of technical capabilities in facilitating digital transformation. Managerial support also has a significant positive effect on adoption readiness ($\beta = 0.28$, $p < 0.001$), indicating that leadership commitment plays an important role in enabling digital innovation initiatives. In contrast, investment uncertainty has a negative effect on adoption readiness ($\beta = -0.21$, $p < 0.001$), suggesting that financial risk perceptions discourage organisations from investing in digital twin technologies. Overall, these findings indicate that digital twin adoption in logistics organisations depends primarily on perceived technological benefits, workforce digital capabilities and leadership

TABLE 6: Regression results for digital twin adoption readiness (N = 500).

Variable	Beta	*t*-value	*p*-value
Perceived benefits	0.42	9.11	< 0.001
Digital skills	0.33	7.24	< 0.001
Managerial support	0.28	5.62	< 0.001
Investment uncertainty	-0.21	-4.12	< 0.001

Note: Dependent variable = digital twin adoption readiness.

commitment, while financial uncertainty remains a key barrier to implementation.

Model diagnostics

To assess the robustness and statistical validity of the regression model, several diagnostic tests were conducted.

These diagnostics evaluate the explanatory power of the model, overall statistical significance, and potential multicollinearity among the independent variables. The model summary statistics indicate that the regression model provides a strong explanation of digital twin technology adoption readiness among logistics organisations.

The model produces an R^2 value of 0.54, indicating that approximately 54% of the variance in adoption readiness is explained by the independent variables included in the model. The adjusted R^2 value of 0.53 suggests that the explanatory power of the model remains stable after accounting for the number of predictors.

The overall regression model is statistically significant, as indicated by an F-statistic of 85.12 ($p < 0.001$). This result confirms that the independent variables collectively contribute to explaining variation in organisational readiness for digital twin adoption. In addition to model summary statistics, multicollinearity diagnostics were examined using VIF values. All VIF values are well below the commonly accepted threshold of 5, indicating that multicollinearity does not pose a concern in the regression model. These results confirm that the independent variables included in the model are sufficiently independent and suitable for regression analysis. Overall, the diagnostic results, as summarised in Table 7, indicate that the regression model is statistically reliable and provides a robust explanation of the determinants of digital twin technology adoption readiness in the logistics sector.

Robustness tests

To further verify the stability of the regression results, additional robustness tests were conducted. Robustness testing examines whether the estimated relationships remain consistent when alternative model specifications are used. This step strengthens confidence in the empirical findings and ensures that the observed effects are not driven by model specification bias. A hierarchical regression approach was employed to test the robustness of the model. In the first model specification (Model 1), perceived benefits were included as the only predictor of digital twin adoption readiness. In the second model (Model 2), digital workforce skills were added to the model to examine whether technological capability improves explanatory power. In the third model (Model 3), managerial support and investment uncertainty were introduced to evaluate the full conceptual model.

TABLE 7: Regression model diagnostics.

Statistic	Value
R^2	0.54
Adjusted R^2	0.53
F-statistic	85.12
Significance (p-value)	< 0.001
Number of observations	500

The results remain consistent across all model specifications. Perceived benefits show a strong positive effect on adoption readiness in all models, indicating that organisations recognising the operational advantages of digital twin technology are significantly more likely to adopt it. Digital workforce skills also demonstrate a consistent positive influence on adoption readiness when introduced in Model 2 and remain significant in Model 3.

Managerial support further strengthens the model in the final specification, confirming that leadership commitment plays a critical role in enabling digital transformation initiatives. In contrast, investment uncertainty shows a negative relationship with adoption readiness, indicating that concerns regarding financial risk and uncertain ROI may discourage organisations from implementing digital twin technologies. The explanatory power of the model increases progressively as additional variables are introduced. Model 1 explains 32% of the variance in adoption readiness. When digital workforce skills are added in Model 2, the explanatory power increases to 47%. The full model (Model 3) explains approximately 54% of the variance in adoption readiness, confirming the importance of both organisational and technological factors in shaping digital twin adoption decisions.

Overall, as summarised in Table 8, the robustness tests confirm that the main regression findings are stable across alternative model specifications. Perceived benefits, digital workforce skills and managerial support consistently emerge as significant predictors of digital twin technology adoption readiness, while investment uncertainty remains a significant barrier. These results strengthen the validity of the empirical findings and support the conclusions of the study.

Discussion

The findings offer three Egypt-specific insights. Firstly, digital twin awareness is growing but uneven across logistics subsectors and organisational roles. Secondly, adoption readiness depends strongly on perceived operational value, workforce digital skills and managerial support. Thirdly, investment uncertainty remains a barrier that may prevent firms from moving from interest to implementation.

TABLE 8: Robustness regression models for digital twin adoption readiness.

Variable	Model 1	Model 2	Model 3
Perceived benefits	0.38***	0.40***	0.42***
Digital skills	-	0.31***	0.33***
Managerial support	-	-	0.28***
Investment uncertainty	-	-	-0.21**
R^2	0.32	0.47	0.54
Adjusted R^2	0.31	0.46	0.53

Note: Dependent variable = digital twin adoption readiness.
**, $p < 0.01$; ***, $p < 0.001$.

For Egypt's logistics sector, the strongest perceived benefits relate to route optimisation, predictive maintenance and inventory visibility. These areas match the operational needs of firms working in port-linked logistics, warehousing, freight forwarding and last-mile delivery. The findings suggest that professionals view digital twins mainly as tools for operational control and decision support, rather than as broad digital transformation symbols (Ivanov 2023; Okimi 2025). The regression results support the TAM logic that perceived usefulness matters for adoption readiness. However, perceived value alone is not enough. Digital skills and managerial support also shape readiness, showing that digital twin adoption is an organisational capability issue. This finding strengthens the paper's readiness argument and separates it from studies that examine implementation maturity or post-adoption performance.

Digital workforce skills also emerge as a strong predictor of adoption readiness (Zaidi, Khan & Chaabane 2024). Organisations with stronger capabilities in data analytics, IoT integration, and simulation modelling report higher readiness levels. These findings highlight the importance of human capital in digital transformation processes. Even when technological solutions are available, organisations may struggle to implement them without sufficient technical expertise among employees. Managerial support represents another significant factor influencing adoption readiness (Le & Fan 2024). Leadership commitment appears to play a critical role in enabling digital transformation initiatives within logistics organisations. Managers who recognise the strategic value of digital technologies are more likely to allocate resources, support experimentation and promote organisational learning related to new digital systems. In contrast, investment uncertainty negatively affects adoption readiness (Benhamou et al. 2026). Many respondents express concerns regarding the financial return of digital twin implementation. This barrier reflects the capital-intensive nature of logistics operations, where firms often prioritise technologies with clear short-term returns. Digital twins often generate benefits through operational efficiency, resilience and improved decision making, which may be difficult to quantify during early implementation stages. Taken together, these findings suggest that digital twin adoption in logistics is shaped by a combination of technological awareness, organisational capabilities and managerial commitment (Freese & Ludwig 2025; Malekzadeh, Torabi & Sheikhalishahi 2025). The results support the view that digital transformation is a socio-technical process rather than a purely technological transition. Successful adoption requires both technical infrastructure and organisational readiness.

The findings provide practical implications for logistics firms and policymakers. Logistics firms should begin with high-value use cases, such as route planning, predictive maintenance and warehouse visibility, because these applications are easier to link to operational benefits. Managers should also invest in employee skills in data analytics, IoT integration, and simulation modelling. Policymakers can support adoption by encouraging university–industry training, pilot funding and digital logistics platforms that reduce uncertainty for smaller firms. These actions can help Egypt's logistics sector move from digital twin awareness to adoption readiness.

Conclusion

This study examined the organisational conditions shaping digital twin adoption readiness in Egypt's logistics sector. Based on survey evidence from 500 logistics professionals, the findings show that readiness is shaped by perceived operational benefits, digital workforce skills, managerial support and investment uncertainty. Perceived benefits had the strongest positive effect, followed by digital skills and managerial support, while investment uncertainty reduced readiness.

The study contributes by focusing on the readiness stage before full implementation. This distinction matters because many logistics firms may recognise the value of digital twins but still lack the skills, leadership support or investment clarity needed to adopt them. For Egyptian logistics firms, readiness-building should begin with practical use cases that show clear operational value, supported by workforce training and senior management commitment.

The study also has policy relevance. Egypt's logistics transformation requires more than infrastructure expansion.

It also requires digital skills, data governance, pilot programmes and stronger links between logistics firms, universities and technology providers. These actions can reduce uncertainty and support the gradual adoption of digital twins across ports, freight forwarding, warehousing and last-mile delivery.

The study has limitations. It uses self-reported survey data and convenience sampling, which may limit generalisability. The cross-sectional design also prevents conclusions about changes in readiness over time.

Future research could use longitudinal data, probability-based sampling and comparative studies across logistics subsectors or countries. Overall, the findings suggest that Egypt's next stage of logistics digital transformation will depend on moving from awareness to structured readiness through skills, leadership support, data infrastructure and lower investment uncertainty.

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CRediT authorship contribution

Islam El-Nakib: Conceptualisation, Data curation, Formal analysis, Funding acquisition, Methodology, Resources, Software, Supervision, Validation, Writing – original draft. Sara Elzarka: Conceptualisation, Data curation, Formal analysis, Funding acquisition, Methodology, Resources, Software, Supervision, Validation, Writing – original draft. All authors reviewed the article, contributed to the discussion of results, approved the final version for submission and publication, and take responsibility for the integrity of its findings.

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Data availability

The anonymised survey data supporting the findings of this study are available from the corresponding author, Islam El-Nakib, upon reasonable request, subject to confidentiality restrictions.

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