

DIGITAL TWIN TECHNOLOGY AND SUSTAINABLE CONSTRUCTION LOGISTICS IN SAUDI ARABIA: A CONCEPTUAL MODEL

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Abstract

The construction sector in Saudi Arabia faces complex logistical challenges, from extreme weather and intricate supply chains to the rapid pace of urban development. Traditional logistics approaches often lead to inefficiencies, delays, and higher costs. This research explores the role of Digital Twin in improve sustainable construction logistics in Saudi Arabia. Digital Twins enable real-time data analysis, improving decision-making and resource allocation, while predictive analytics can forecast demand, mitigate supply chain disruptions, and enhance inventory management. The study develops the S-Twin Model (Sustainability-Twin Model), tailored to the Saudi construction sector's needs. Data from stakeholder surveys and project observations in-form strategies for supply chain optimization, efficient materials handling, and sustainable transport solutions. The proposed model supports dynamic adaptation and integration of sustainability goals, offering actionable insights for industry stakeholders. The aim is to establish a smart, sustainable logistics framework that drives efficiency, resilience, and environmental responsibility in construction.

Keywords: Construction, Logistics, Digital Twin, Sustainability

1. Introduction

The integration of Digital Twin (DT) technology into construction logistics is poised to revolutionize the sector (Greif et al., 2020), particularly in developing countries such as Saudi Arabia. Digital Twins, which create real-time virtual models of physical systems, offer significant enhancements in planning, monitoring, and management throughout the lifecycle of construction projects. According to Ivanov and Gusikhin (2024), DTs can substantially improve decision-making processes, operational efficiency, and strategic planning within logistics and supply chain systems. By providing a platform for real-time tracking, scenario simulation, and predictive analysis, DTs enhance transparency and resilience, enabling better handling of disruptions caused by events such as natural disasters or geopolitical conflicts. These capabilities are crucial for maintaining

operational continuity and adapting to rapid changes in the supply chain environment, which are becoming increasingly complex due to globalization and technological advancements (Zahedi et al., 2024; Zhu et al., 2023).

In the context of construction logistics, Gehring and Rüppel (2023) highlight the inefficiencies that currently plague construction site logistics and propose a solution through a digital construction logistics twin. This twin integrates data from various sources, including Building Information Modeling (BIM), technical specifications, and supplier telemetry data. By offering a comprehensive overview of logistics processes, the digital twin reduces the need for manual data entry and improves the transparency and efficiency of material management on construction sites. The practical implementation of DTs in construction logistics, however, faces several significant

challenges. In another study, Ivanov and Gusikhin (2024) emphasize the need for advanced analytics and modeling techniques, data standardization, and robust cybersecurity measures to support DT operations. Whilst studies continue to advance the application of Digital Twins within construction operations, and particularly construction logistics, studies on how this is interlinked with sustainable outcomes (e.g. Sustainability Development Goals) are considerably limited. For instance, in a recent study by Moshood et al. (2024), it was highlighted that DT technology should act as a foundation for a data-driven lifecycle that accumulates diverse data/information to facilitate informed decision-making (Paddeu et al., 2024; Mayouf, et al., 2024). More importantly, DT capabilities would enable more informed business models that directly impact various dimensions within construction projects, hence the need to align data generated to inform more sustainable outcomes.

Addressing these challenges through continued research and development is crucial to fully leverage the benefits of DT technology, making construction logistics more sustainable and resilient. The future of DT computation involves integrating advanced analytics, machine learning, and simulation techniques to enhance the predictive and prescriptive capabilities of digital twins. By doing so, DTs can provide deeper insights into logistics operations, identify potential bottlenecks before they occur, and suggest optimal solutions to mitigate risks. This proactive approach to logistics management is particularly valuable in the construction sector, where delays and inefficiencies can lead to significant cost overruns and project delays. Overall, the literature underscores the transformative potential of Digital Twins in revolutionizing construction logistics management in Saudi Arabia, highlighting both the opportunities and the challenges that lie ahead. Thus, this research aims to shed the light on the potential of digital twins in improving sustainable integration within construction logistics using Digital Twin technology.

This study aims to build on these insights by empirically investigating how Digital Twin (DT) technology can improve sustainable construction logistics in Saudi Arabia. This study intends to close the gap between theoretical possibilities and real-world applications by creating a Digital Twin framework focused on sustainability, specifically designed for the logistical challenges of the local construction industry. Consequently, this study is directed at the following objectives:

1- To assess the current state of construction logistics practices in Saudi Arabia, with particular focus on supply chain efficiency, material handling, and transportation methods.

2- Evaluate stakeholder awareness and readiness for adopting Digital Twin technologies and sustainable logistics solutions within diverse construction sectors.

3- To develop and validate the S-Twin Model, a framework for integrating Digital Twin technology into construction logistics with the aim of enhancing sustainability and operational performance.

2. Literature Review

2.1. Construction Logistics and Sustainability

Construction logistics plays a crucial role in ensuring efficient project delivery while minimizing environmental and societal impacts. As construction projects increasingly take place in urban environments, logistics challenges such as traffic congestion, noise pollution, and CO2 emissions become more prominent (Dhawan et al., 2023). Urban freight data indicate that construction logistics contribute significantly to emissions and vehicle congestion, necessitating the adoption of sustainable practices to address these challenges (Olivari et al., 2025).

Several strategies have emerged to promote sustainability in construction logistics. Construction Consolidation Centres (CCCs), which centralize material distribution, have shown significant promise in reducing vehicle trips and emissions while improving delivery reliability (Haag & Jünger, 2023). However, their adoption faces barriers such as high setup costs, limited scalability, and the need for robust stakeholder collaboration (Morel et al., 2020). Electric and hybrid vehicles, as well as alternative fuel sources, have also been identified as essential components of sustainable construction logistics, offering opportunities to align logistics activities with climate goals (Chelstowska et al., 2025; Olivari et al., 2025).

Advanced decision-making frameworks, such as multi-criteria analysis and life cycle assessment tools, are increasingly utilized to integrate sustainability into logistics planning. Lagorio et al. (2016) argue that these frameworks help balance economic, environmental, and social objectives, providing a roadmap for decision-makers to prioritize sustainability without compromising efficiency. Yet, as noted by Janné (2020), the fragmented nature of the construction industry remains a significant obstacle to fully embedding sustainability into logistics practices. This fragmentation often results in inefficiencies, such as poor coordination between suppliers, contractors, and clients, further compounding environmental and operational challenges.

Emerging trends in circular construction have the potential to further reduce the environmental

footprint of logistics operations. Circular logistics focuses on reusing and recycling materials within the construction lifecycle, thus reducing the demand for virgin resources and minimizing waste. Recent research (e.g. Eriksson and Fredriksson, 2025; Belfadel et al., 2023) shed the light on the importance of circularity principles, and how it reshape logistics networks, emphasizing localized resource loops and reducing transportation distances. However, implementing circular logistics requires robust digital infrastructure and stakeholder alignment, which are often lacking in many regions, including Saudi Arabia.

2.2. Digital Twin Technology in Construction Logistics

Digital Twin (DT) technology has emerged as a transformative solution to address the inefficiencies and complexities of construction logistics. DTs enable the creation of real-time virtual replicas of physical systems, integrating diverse data streams to enhance planning, monitoring, and decision-making processes (Omrany et al., 2023). This capability is particularly relevant in logistics, where delays, material mismanagement, and resource waste are persistent challenges. Applications of DTs in construction logistics include real-time tracking of material flow, predictive maintenance of equipment, and dynamic scheduling of deliveries to optimize resource utilization (Saif et al., 2024). For instance, Zhang et al. (2024) discuss how DTs can be used to synchronize supply chain operations, reducing bottlenecks and improving delivery reliability. Additionally, it was highlight that DT-enabled analytics can predict potential disruptions, allowing proactive mitigation strategies that enhance project resilience (Bakhshi et al., 2024).

Despite these benefits, the widespread adoption of DTs in construction logistics faces significant barriers (Long et al., 2024). Key challenges include the lack of standardized data formats, high implementation costs, and concerns over data security and privacy (Zhang et al., 2024). Recent research (e.g. Dhawan et al., 2023; Yang et al., 2024) emphasizes that the fragmented nature of the construction industry exacerbates these challenges, as stakeholders often operate in silos, using incompatible tools and systems. Addressing these barriers requires the development of interoperable platforms that facilitate seamless data exchange across the supply chain.

The integration of DTs with other emerging technologies, such as blockchain and Internet of Things (IoT), offers additional opportunities to enhance logistics efficiency. Blockchain technology, with its capabilities in secure data

sharing and traceability, can address trust and transparency issues in supply chain operations (Zhang et al., 2024). Similarly, IoT devices, such as smart sensors and RFID tags, can provide real-time data inputs to DT systems, enabling accurate and dynamic modeling of logistics processes (Yang et al., 2023). These synergies highlight the potential for DT ecosystems to revolutionize construction logistics, particularly in large-scale projects.

2.3. Implications for Saudi Arabia's Construction Sector

Saudi Arabia's Vision 2030 initiative has set ambitious goals for infrastructure development, driving demand for innovative and efficient logistics systems. However, the rapid pace of urbanization and the scale of ongoing projects have exposed significant logistical inefficiencies, including congestion, inconsistent delivery schedules, and poor resource utilization (Haag & Jünger, 2023). Addressing these inefficiencies is critical to ensuring the timely and sustainable delivery of infrastructure projects.

Digital Twin technology offers a pathway to overcoming these challenges by providing real-time insights and predictive analytics that improve logistics planning and execution. For example, DTs can optimize material delivery schedules based on traffic patterns, reducing delays and emissions associated with idle vehicles (Omrany et al., 2023). Additionally, the integration of DTs with urban mobility systems can enhance last-mile logistics, a critical component of urban construction projects (Olivari et al., 2025).

The adoption of DTs in Saudi Arabia's construction sector must also align with broader sustainability goals. By leveraging DT capabilities to monitor emissions, waste generation, and resource consumption, stakeholders can ensure that logistics operations contribute to achieving the Sustainable Development Goals (SDGs). Gonzalez-Feliu et al. (2014) argue that such alignment is essential for fostering long-term resilience and competitiveness in the construction sector. Policy frameworks play a vital role in facilitating the adoption of DTs and sustainable logistics practices. Collaborative governance models, as proposed by Morel et al. (2020), provide a roadmap for engaging stakeholders, setting standards, and incentivizing innovation. Public-private partnerships, in particular, can accelerate the deployment of DT-enabled systems by sharing risks and resources across sectors. For example, initiatives to establish Construction Consolidation Centres (CCCs) in Saudi Arabia could benefit from DT integration, enabling dynamic management of materials and reducing urban congestion.

Whilst there are many progressive efforts within

the construction sector, managing logistics while integrating sustainability across various scales remains a major challenge. More importantly, despite the benefits that advanced technologies such as Digital Twins offer, there needs to be focus on expanding the applicability of DTs in diverse project contexts, from small-scale residential developments to mega-projects. Exploring the intersection of DT technology with sustainability metrics, and in particular, how it can be integrated as part of managing construction logistics within a continually growing construction/infrastructure projects, such as Saudi Arabia, is paramount. Therefore, this research will explore how digital twins can support an improved integration of sustainability in construction logistics in Saudi construction projects.

3. Methodological Approach

For the purpose of this research, a mixed-method approach is adopted, combining quantitative and qualitative methods to investigate the integration of Digital Twin (DT) technology and sustainability practices in construction logistics within Saudi Arabia. Mixed-method research is well-suited to complex studies as it enables a comprehensive exploration of both measurable attributes and the contextual factors influencing them (Creswell & Plano Clark, 2017). By employing both questionnaire surveys and field observations, this study ensures triangulation of data, enhancing the reliability and validity of its findings (Flick, 2018). This approach allows for a holistic understanding of the challenges and opportunities present in Saudi Arabia's construction logistics. Specifically, the study design was consistent with the three research goals. The quantitative aspect, which involves a structured questionnaire survey, addresses Objectives 1 and 2 by evaluating current logistics practices and stakeholders' views on digital transformation and sustainability. Meanwhile, the qualitative aspect, which includes field observations, supports Objective 3 by exploring real-world logistics operations and confirming elements of the proposed S-Twin Model.

The primary data collection tool was a questionnaire survey targeting 150 – 200 participants, where in total, 150 stakeholders responded, including project managers, logistics coordinators, supply chain managers, and construction site supervisors. The questionnaire was designed to explore key dimensions such as supply chain efficiency, materials handling, transportation logistics, and sustainability integration. Stratified random sampling was employed to ensure representation across various

construction sectors, such as residential, commercial, and infrastructure projects, thereby reflecting the diversity of logistical operations in the Saudi Arabian construction industry (Bryman, 2015). The questionnaire comprised both closed-ended questions, which facilitated quantitative analysis, and open-ended questions, enabling the capture of qualitative insights. A pilot study involving ten participants was conducted to refine the survey instrument, ensuring clarity and relevance. The pilot study also confirmed that the survey aligned with the study's objectives and eliminated ambiguities in question phrasing.

To complement the survey data, field observations were conducted at selected construction sites to gain practical insights into logistics operations. Observation is a powerful tool in logistics research as it allows for the direct examination of real-world processes and practices, providing context-rich data that surveys alone cannot capture. In total, two sites were chosen to represent various project scales and logistical complexities, including urban residential projects with constrained spaces and large-scale infrastructure projects with extensive supply chain networks. Observations were guided by a structured checklist that systematically captured details about logistics processes, material handling efficiency, transportation methods, and sustainability practices. This checklist ensured consistency in data collection and minimized observer bias (O'Reilly & Kiyimba, 2015). To provide further clarity, Figure 1 illustrates the research design employed for this study.

Quantitative data from the surveys were analyzed using descriptive statistics to provide an overview of trends, such as the prevalence of logistical inefficiencies and the level of technology adoption, while inferential analysis explored relationships between variables, such as the correlation between stakeholder roles and perceptions of sustainability integration (Fowler, 2014). Qualitative data from open-ended survey responses and field observations were subjected to thematic analysis, which identified key patterns and themes across the data (Braun & Clarke, 2006). Quantitative data obtained from the questionnaire were analyzed using SPSS software, while qualitative data were derived from open-ended responses and field notes with the assistance of NVivo 12 software.

Finally, ethical approval for this study was granted by the Institutional Review Board, and all participants provided informed consent before any data were collected. We ensured strict adherence to the ethical guidelines for research involving human subjects by maintaining participant confidentiality and data privacy.

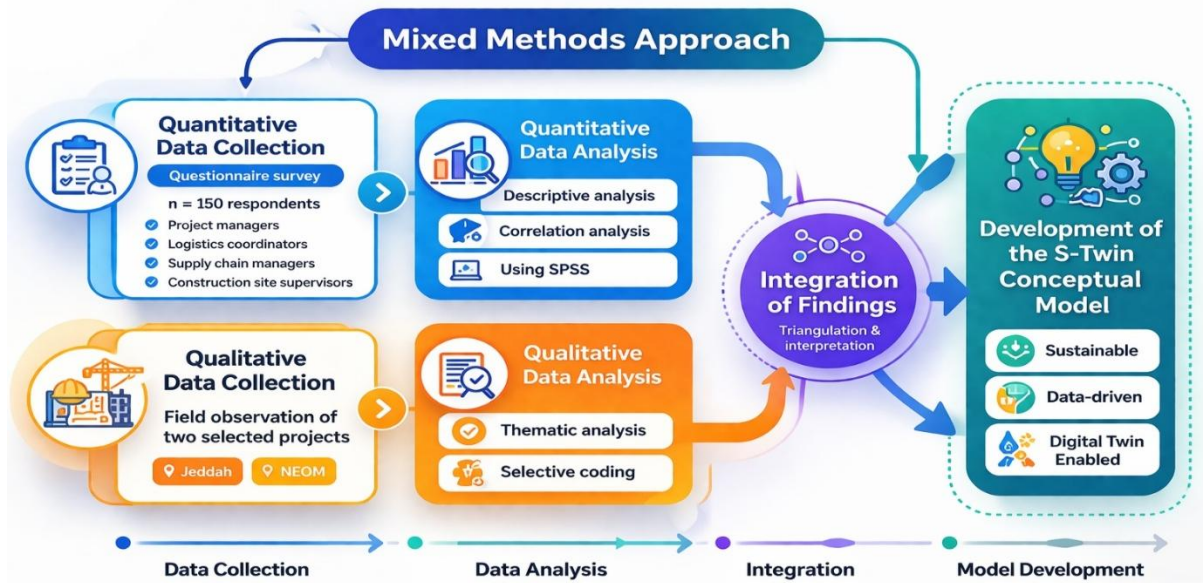


Figure 1: Research design (Authors, 2026)

4. Results and Analysis – Quantitative Analysis

This section presents the findings from the research conducted in Saudi Arabia on enhancing efficiency and sustainability in construction supply chain management. The data was collected from 150 respondents through a questionnaire that focused on logistics coordination, material handling efficiency, sustainability practices, and the adoption of new technologies. The results are outlined below, showcasing key trends and opportunities for improving both efficiency and sustainability in construction supply chains in the GCC.

The first part outlines the demographic details of the survey participants, emphasizing their roles in the construction sector and their levels of

experience. These attributes are crucial for understanding the results of logistics, technology implementation, and sustainable practices. Figure 1 demonstrates that contractors comprise the largest group of respondents at 48.7%, with consultants at 18.7%, subcontractors at 12%, and the remaining 20% comprising roles such as suppliers, site engineers, and logistics coordinators. This distribution shows a broad representation of key stakeholders in construction supply chain activities. The notable presence of contractors is particularly significant as they frequently manage logistics and material handling on-site, enabling them to provide valuable perspectives on operational efficiency and challenges.

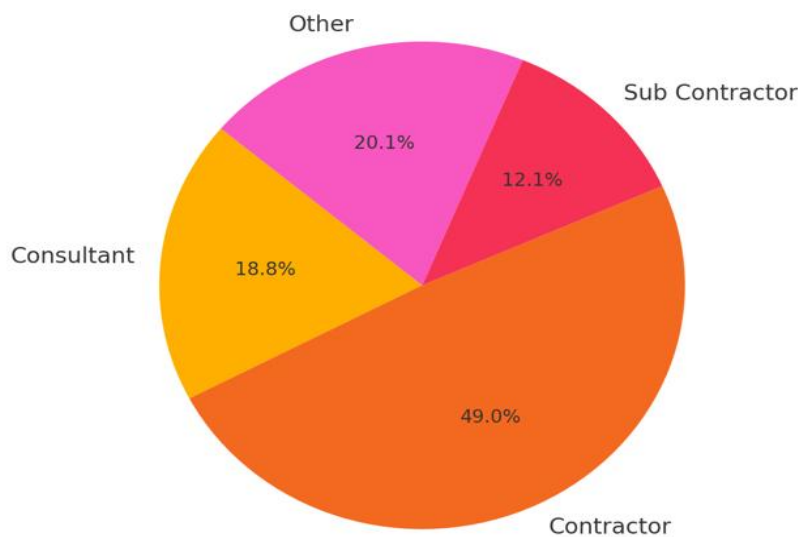


Figure 2: Distribution of roles of respondents

Figure 2 demonstrates that contractors comprise the largest group of respondents at 48.7%, with consultants at 18.7%, subcontractors at 12%, and the remaining 20% comprising roles such as

suppliers, site engineers, and logistics coordinators. This distribution shows a broad representation of key stakeholders in construction supply chain activities. The notable presence of

contractors is particularly significant as they frequently manage logistics and material handling on-site, enabling them to provide valuable perspectives on operational efficiency and challenges. Figure 3 illustrates the distribution of respondents according to their professional experience. Interestingly, 36.7% of the participants indicated that they had over 10 years of experience, 26.7% had been in the field for 6–10 years, 23.3% for

2–5 years, and 13.3% for less than 2 years. A substantial proportion of experienced professionals lends credibility to the data, as these individuals are likely to be familiar with the evolving challenges and practices in construction logistics. This range of experience ensures that the study reflects insights from both experts and new professionals in the industry.

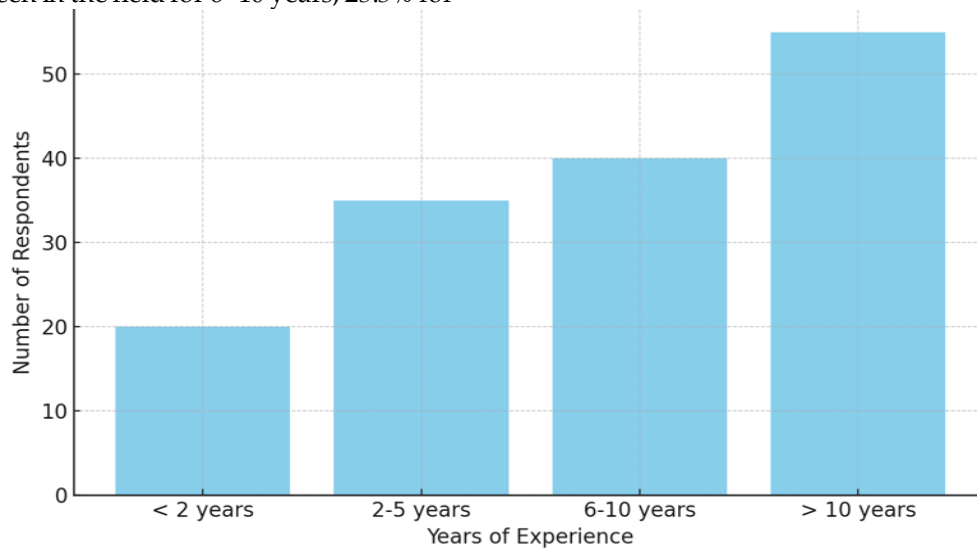


Figure 3: Respondents’ Years of Experience

4.1 Nature of Construction Projects and Logistics Scope

This section examines the various types of construction projects managed by respondents and highlights the main challenges they encounter when managing supply chains. These findings offer insights to comprehend how project characteristics affect the complexity of logistics and the implementation of sustainable practices.

4.1.1 Types of Construction Projects Handled

Figure 4 demonstrates that most participants were involved in residential (36.4%) and commercial

(32.6%) construction projects, highlighting them as the leading sectors in the current Saudi market. Infrastructure projects accounted for 18.8% of the total projects, showing considerable activity in transportation and public work. Although industrial projects were the least represented (12.3%), they underscored the presence of more specialized construction activities. This distribution indicates a well-rounded dataset with strong representation from sectors in which logistics complexity and sustainability are becoming increasingly crucial.

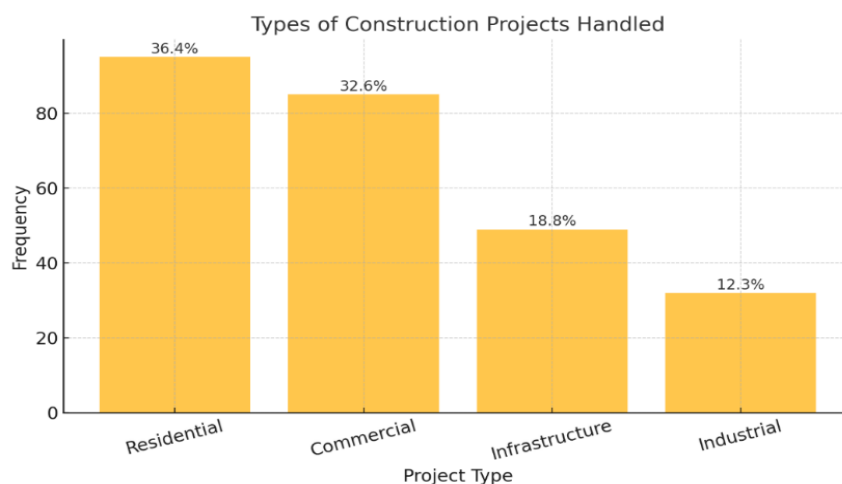


Figure 4: Common Types of Construction Projects in Saudi Arabia

4.1.2 Common Challenges in Supply Chain Management

Numerous persistent challenges have been identified in the management of construction supply chains. Figure 5 illustrates the most frequently reported challenges, with transportation delays (26%) and supplier reliability issues (25.7%) being the most prominent,

indicating frequent disruptions in material flow and scheduling. Cost fluctuations (24.3%) and material shortages (24%) are also significant concerns, reflecting the impact of market volatility on procurement and planning. These findings underscore the need for more resilient, flexible, and well-coordinated supply chain strategies.

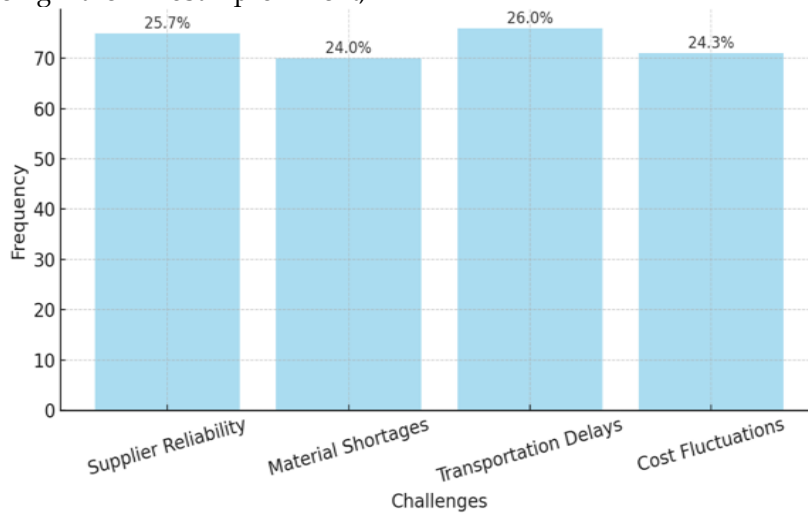


Figure 5: Common Challenges in Supply Chain Management

4.2 Logistics Coordination and Operational Challenges

Efficient logistics coordination is critical to the success of construction projects, particularly when multiple suppliers, contractors, and subcontractors are involved. This section examines the operational challenges reported by respondents, focusing on logistics coordination, transportation delays, logistics efficiency, and specific obstacles related to transportation. These factors directly influence project timelines, cost control, and overall supply chain performance.

4.2.1 Challenges in logistics coordination

As shown in Figure 6, a significant number of respondents (53.3%) found it moderately to extremely challenging to coordinate logistics across multiple suppliers and contractors. Furthermore, 15.3% rated logistics coordination as very challenging, underscoring the complexity involved in aligning multiple stakeholders in construction supply chains. This result points to a significant area of concern that could be addressed through better collaboration tools and streamlined processes.

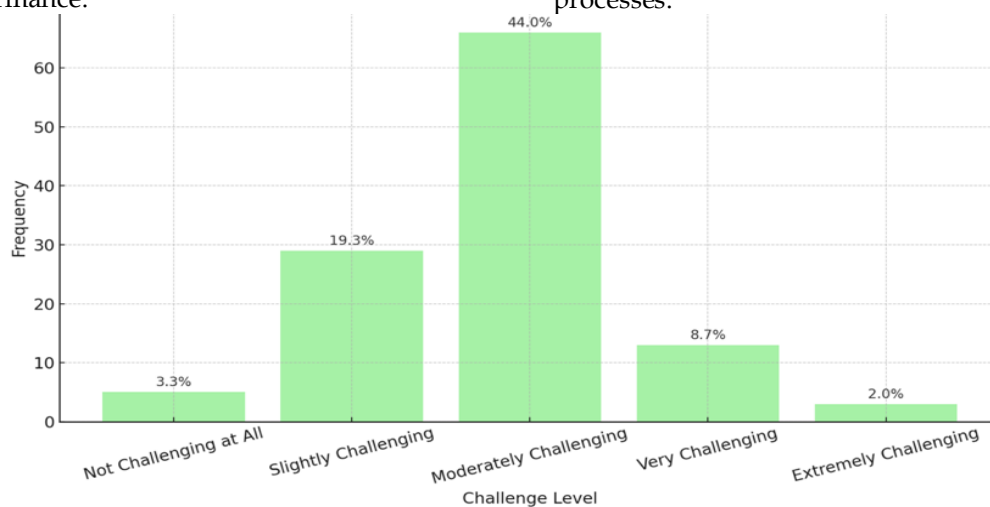


Figure 6: Challenges in logistics coordination that face construction projects in Saudi Arabia

4.2.2 Impact of transportation delays

As seen in Figure 7, Transportation delays were identified as a frequent issue, with 50.7% of respondents reporting that delays

occurred sometimes and 16% stating that they occurred often. Only a small portion of respondents (6%) indicated that transportation delays never impacted their logistics. This finding

emphasizes the need for better transport coordination to prevent supply chain bottlenecks

and the associated project delays or cost escalations.

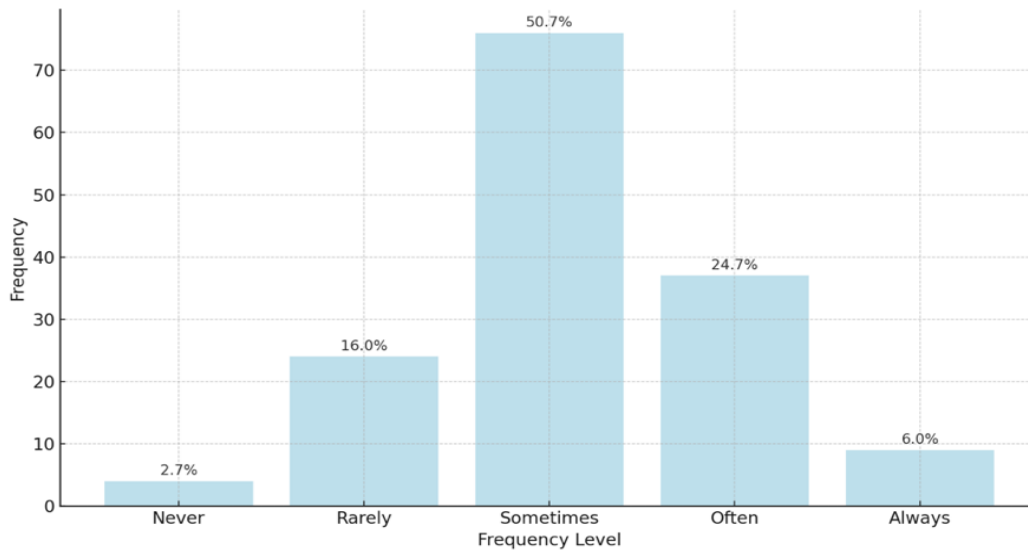


Figure 7: Impact of transportation delays

Figure 7: Impact of transportation delays on construction projects in Saudi Arabia

4.2.3 Challenges in Transportation logistics

Transportation logistics efficiency followed a similar pattern, with the majority of respondents (58%) rated transportation logistics efficiency as average. Only 22% rated their transportation logistics as efficient, and a smaller percentage (6%) rated it as very efficient. These findings suggest that transportation logistics could benefit from optimization efforts, particularly in areas like route planning and real-time monitoring to improve timely deliveries. Additionally, several key challenges emerged in transportation logistics, with traffic congestion identified as the most frequently encountered issue. Respondents reported that traffic delays significantly impacted the timely delivery of materials to construction sites, causing disruptions in the supply chain. Vehicle maintenance was another area of concern, with some respondents noting that poorly maintained fleets often led to breakdowns, further delaying material deliveries. Regulatory compliance was also highlighted, particularly in international projects where differing regulations across borders can create bottlenecks. These findings suggest that improving route optimization and vehicle maintenance, along with better regulatory navigation, could enhance transportation logistics efficiency.

4.3 Materials Handling and Technological Practices

Material handling is a key logistical function in construction, affecting site productivity and project

management. This section explores how efficiently materials are managed, the challenges faced during handling, and the extent to which technology is being utilized. These insights help identify opportunities for improving operational workflows through digital solutions. When asked about the efficiency of their current materials handling processes, nearly half of the respondents (48.7%) rated these processes as average. However, 28% rated their processes as efficient, indicating that some organizations have achieved reasonable success in streamlining materials handling. Conversely, 12% of respondents rated their materials handling as inefficient, suggesting room for improvement in managing materials flow within the supply chain.

The results indicate that labour skills were a significant challenge in materials handling, with respondents noting a shortage of trained personnel capable of managing advanced handling systems. Space constraints on construction sites were another critical issue, especially in urban projects where storage space for materials is limited. Additionally, safety concerns were highlighted, as the improper handling of heavy materials increases the risk of workplace accidents. These findings underscore the need for both increased training and better planning to optimize materials handling processes. Technology adoption in materials handling varied widely, with only 10% of respondents stating they always used technology such as automated systems or real-time tracking. The majority of respondents (35.3%) indicated they sometimes used technology, while 21.3% used it rarely. These findings suggest that while technology is becoming increasingly

important in managing supply chains, many organizations are still in the early stages of full-scale technology adoption.

4.4 Sustainability Practices in construction logistics in Saudi Arabia

Technology adoption in materials handling varied widely, with only 10% of respondents stating they always used technology such as automated systems or real-time tracking. The majority of respondents (35.3%) indicated they sometimes used technology, while 21.3% used it rarely. These findings suggest that while technology is becoming increasingly important in managing supply chains, many organizations are still in the early stages of full-scale technology adoption. When it comes to integrating sustainability practices into logistics operations, only 3.3% of respondents reported that sustainability was fully integrated in their operations. The majority (38%) stated that they had achieved moderate integration, while 26.7% reported slight integration of sustainability initiatives. This suggests that while organizations recognize the importance of sustainability, full integration remains a challenge, indicating significant potential for future improvement.

4.4.1 Contribution of construction logistics to SDGs in Saudi Arabia

On the contribution of logistics management to Sustainable Development Goals (SDGs), 28.7% of respondents indicated that their practices had a slight contribution, while 25.3% reported a moderate contribution. Only 4% of respondents felt their practices had an extremely significant contribution to achieving SDGs. This reflects the need for construction supply chains to align more closely with broader sustainability objectives, such as reducing carbon emissions and promoting resource efficiency.

The analysis of Sustainable Development Goals

(SDGs) targeted by logistics management practices reveals significant trends and priorities. As demonstrated in Figure 8, SDG 7: Affordable and Clean Energy ranked the highest, with 70 responses, demonstrating a clear emphasis on integrating renewable energy and energy efficiency solutions within logistics operations. This finding aligns with the growing global focus on sustainable energy practices. Following this, SDG 3: Good Health and Well-being was the second most selected, with 55 responses, highlighting the importance of ensuring health and safety standards in logistics processes to support the well-being of both workers and affected communities.

SDG 9: Industry, Innovation, and Infrastructure closely followed, with 53 responses, reflecting the critical role of innovative technologies and strong infrastructure in enhancing logistics efficiency and sustainability. SDG 12: Responsible Consumption and Production received 47 responses, underscoring efforts to minimize waste and adopt sustainable resource utilization practices in logistics management. Similarly, SDG 11: Sustainable Cities and Communities, with 46 responses, highlights the focus on urban logistics solutions that reduce emissions and congestion, supporting the development of more sustainable cities.

While SDG 15: Life on Land garnered 39 responses, indicating concern for protecting terrestrial ecosystems from the environmental impact of logistics, SDG 13: Climate Action ranked the lowest, with 31 responses. This suggests that while climate action remains a critical global issue, it may not yet be fully integrated into the logistics strategies of respondents. Overall, the ranking reflects a strong focus on energy efficiency, innovation, and well-being, with room for improvement in addressing climate resilience and environmental impacts.

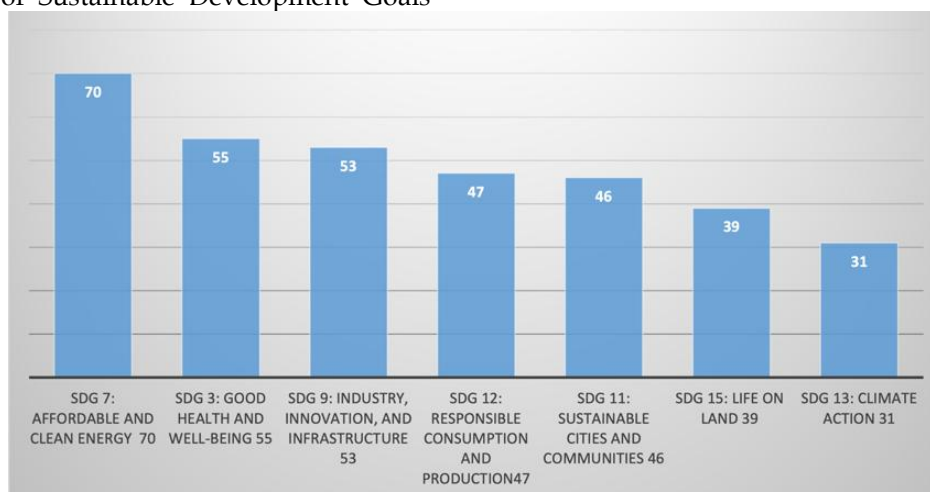


Figure 8: SDGs Supported by Construction Logistics Management Practices in Saudi Arabia

4.4.2 Challenges facing integration of sustainability practices in construction logistics

The analysis of challenges faced in integrating sustainability practices into logistics operations highlights four primary obstacles, as shown in Figure 9. The most significant challenge, as identified by 88 respondents, is the lack of expertise. This suggests that many organizations lack the necessary knowledge and skills to implement sustainable practices effectively. The cost implications associated with adopting sustainability measures rank as the second most significant barrier. This finding underscores the

financial strain that sustainability initiatives can impose, particularly for organizations with limited budgets or competing financial priorities. Regulatory hurdles are another key challenge. This suggests that complex or inconsistent regulations related to sustainability practices can create significant barriers to implementation, deterring organizations from pursuing such initiatives. Lastly, resistance to change was identified as a challenge by 51 respondents. This reflects the difficulty in overcoming organizational inertia and the reluctance of stakeholders to adapt to new sustainability-oriented practices.

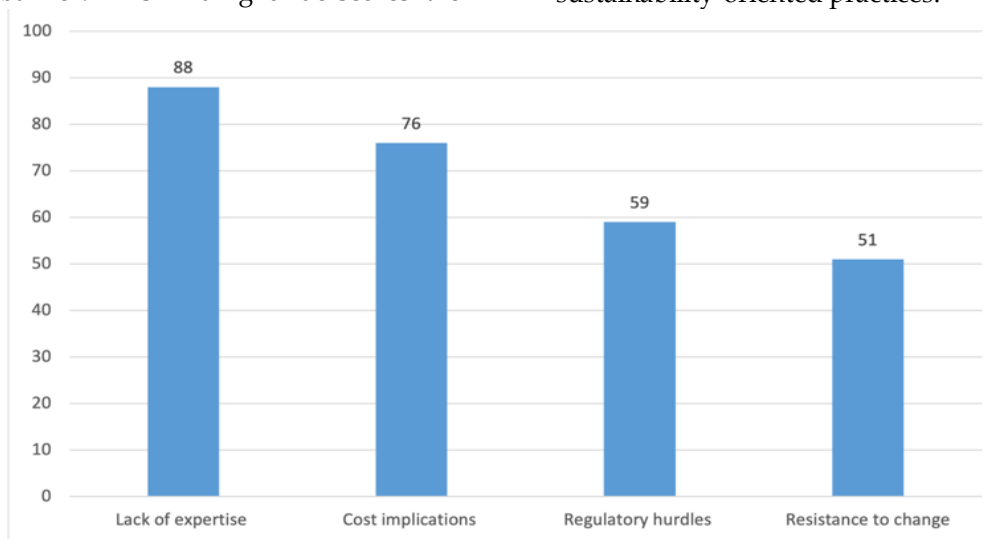


Figure 9: Challenges to Integrating Sustainability Practices

4.5 Technological Readiness and Capacity Building

Digital transformation in construction logistics depends not only on available technologies but also on organizational readiness. This section assesses how open companies are to adopting new logistics technologies and the extent to which they invest in training and workforce development. The results provide insight into the sector's preparedness for digital innovation.

In terms of adopting new technologies for logistics optimization, 36% of respondents were moderately open, while 23.3% were very open to embracing innovative tools and systems. However, 9.3% of respondents indicated that their organizations were not open at all to adopting new technologies, reflecting some resistance to change within the industry. Encouragingly, a significant proportion of respondents recognized the potential of technology to improve efficiency, suggesting that greater emphasis on technology adoption could enhance supply chain management. On the other hand, the frequency of training for new logistics technologies varied across the respondents. While 34.7% reported that they received training sometimes, 20% indicated

they never received training on new technologies. Only 15.3% of respondents stated that they always received training, pointing to a gap in skill development that could impede the broader adoption of technology in logistics management. Respondents identified several key areas for improvement in construction logistics over the next five years. Supply chain transparency emerged as the most critical area, with many noting the importance of tracking materials throughout the supply chain to improve accountability and reduce the risk of delays or mismanagement. Real-time data integration was also highlighted as a priority, with respondents stressing the need for better tools to monitor logistics in real-time, allowing for more informed decision-making and quicker responses to issues. Additionally, the adoption of autonomous systems was viewed as a potential game-changer for improving logistics efficiency, with some respondents expressing interest in using autonomous vehicles and drones for material delivery.

4.6 Advanced Analytics

4.6.1. Kruskal-Wallis Test

The Shapiro-Wilk test was conducted for each variable by project type to assess normality. Based

on the results, none of the variables across the project types were fully normally distributed. As a result, the Kruskal-Wallis test was chosen as the

appropriate non-parametric method for all variables.

Table 1: Kruskal-Wallis Test Across Project Types

	Residential	Commercial	Infrastructure	Industrial
Logistic Coordination	Statistic: 0.192 p-value: 0.661	Statistic: 0.037 p-value: 0.847	Statistic: 1.947 p-value: 0.163	Statistic: 0.049 p-value: 0.825
Transportation delay	Statistic: 3.462 p-value: 0.063	Statistic: 0.785 p-value: 0.375	Statistic: 0.786 p-value: 0.375	Statistic: 0.575 p-value: 0.448
Material handling	Statistic: 0.743 p-value: 0.389	Statistic: 3.069 p-value: 0.080	Statistic: 6.876 p-value: 0.009	Statistic: 3.268 p-value: 0.07
Technology use	Statistic: 2.144 p-value: 0.143	Statistic: 1.565 p-value: 0.211	Statistic: 0.449 p-value: 0.503	Statistic: 0.376 p-value: 0.540
Transportation Logistic effectiveness	Statistic: 0.094 p-value: 0.759	Statistic: 0.927 p-value: 0.336	Statistic: 0.004 p-value: 0.949	Statistic: 0.428 p-value: 0.513

The Kruskal-Wallis test (see Table 1) revealed a significant difference in Material Handling Efficiency for infrastructure projects (H-statistic = 6.876, $p = 0.009$). This suggests that companies involved in infrastructure projects face unique challenges in material handling, likely due to the complexity and scale of materials required for such large-scale operations. The findings indicate that material handling in infrastructure projects requires tailored strategies and interventions to address these distinct logistical demands effectively. In contrast, no significant differences were observed across project types for other variables, including Logistics Coordination, Transportation Delays, Technology Use, and

Transportation Logistics Efficiency. These results suggest that these aspects of logistics management are experienced consistently across residential, commercial, and industrial projects. Companies across these sectors appear to face similar challenges and efficiencies, highlighting a uniformity in logistical issues and practices across diverse construction project types.

4.6.2 Chi-Square Test

The Chi-Square Test (see Table 2) of Independence was conducted to evaluate the relationships between sustainability practices, technological adoption, and organizational/project characteristics.

Table 2: Chi-Square Test

Variable	Chi-Square Statistic	p-value	Result
Sustainability Integration vs. Company Type	23.276	0.025	Significant
Technological Adoption vs. Company Type	11.16	0.515	not significant
Sustainability Integration vs. Residential	1.97	0.74	not significant
Technological Adoption vs. Residential	3.84	0.42	not significant
Sustainability Integration vs. Commercial	4.83	0.30	not significant
Technological Adoption vs. Commercial	3.72	0.44	not significant
Sustainability Integration vs. Infrastructure	10.14	0.037	Significant
Technological Adoption vs. Infrastructure	1.25	0.86	not significant
Sustainability Integration vs. Industrial	4.063	0.39	not significant
Technological Adoption vs. Industrial	5.33	0.25	not significant

As shown in Figure 10 (explained more in section 4.6.3), significant results were observed for Sustainability Integration in relation to Company Type (Chi-Square = 23.276, $p = 0.025$) and Infrastructure projects (Chi-Square = 10.149, $p = 0.038$). These findings indicate that different company roles, such as contractors and consultants, adopt sustainability practices at

varying levels. Similarly, Infrastructure projects demonstrate a stronger focus on sustainability practices compared to other project types, likely due to the unique complexities and demands of these projects. However, no significant relationships were identified for Technological Adoption across either Company Type or project types, suggesting that technology use is consistent

across different organizational roles and projects. Additionally, Sustainability Integration showed no significant relationships with Residential, Commercial, or Industrial projects, indicating a uniform approach to sustainability in these contexts. These results suggest that while sustainability practices vary depending on company role and infrastructure-specific contexts, technological adoption appears to be applied uniformly across the construction industry.

4.6.3 Correlation Analysis

The correlation analysis revealed key relationships between technology use, logistics efficiency,

coordination, and sustainability integration. As illustrated in Figure 10, A moderate positive correlation was observed between Technology Use and Transportation Logistics Efficiency (correlation = 0.35), indicating that frequent use of technology enhances the efficiency of transportation logistics. Additionally, a weak-to-moderate positive correlation (correlation = 0.23) between Technology Use and Material Handling Efficiency suggests that technological adoption slightly improves material handling processes, though the impact is less pronounced.

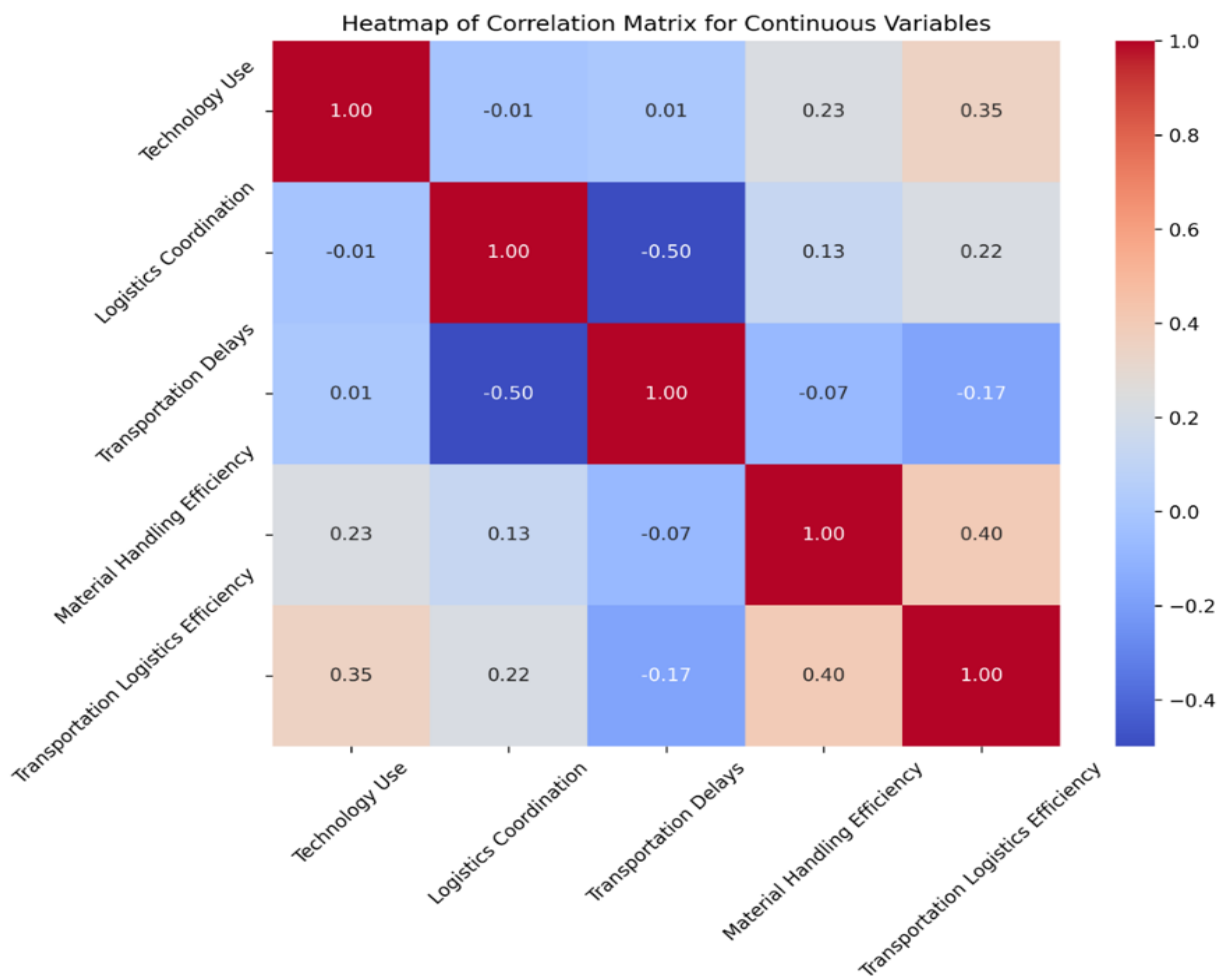


Figure 10: Heatmap of correlation matrix

In terms of logistics coordination, a moderate negative correlation (-0.50) was identified between Logistics Coordination and Transportation Delays, indicating that better coordination is associated with fewer delays. Furthermore, Material Handling Efficiency exhibited a strong positive correlation (0.40) with Transportation Logistics Efficiency, emphasizing that efficient material handling processes significantly improve overall transportation efficiency. According to Figure 11, a weak positive correlation (0.22) was also observed between Logistics Coordination and Transportation Logistics Efficiency, suggesting a smaller, but notable, impact of coordination improvements on transportation efficiency.

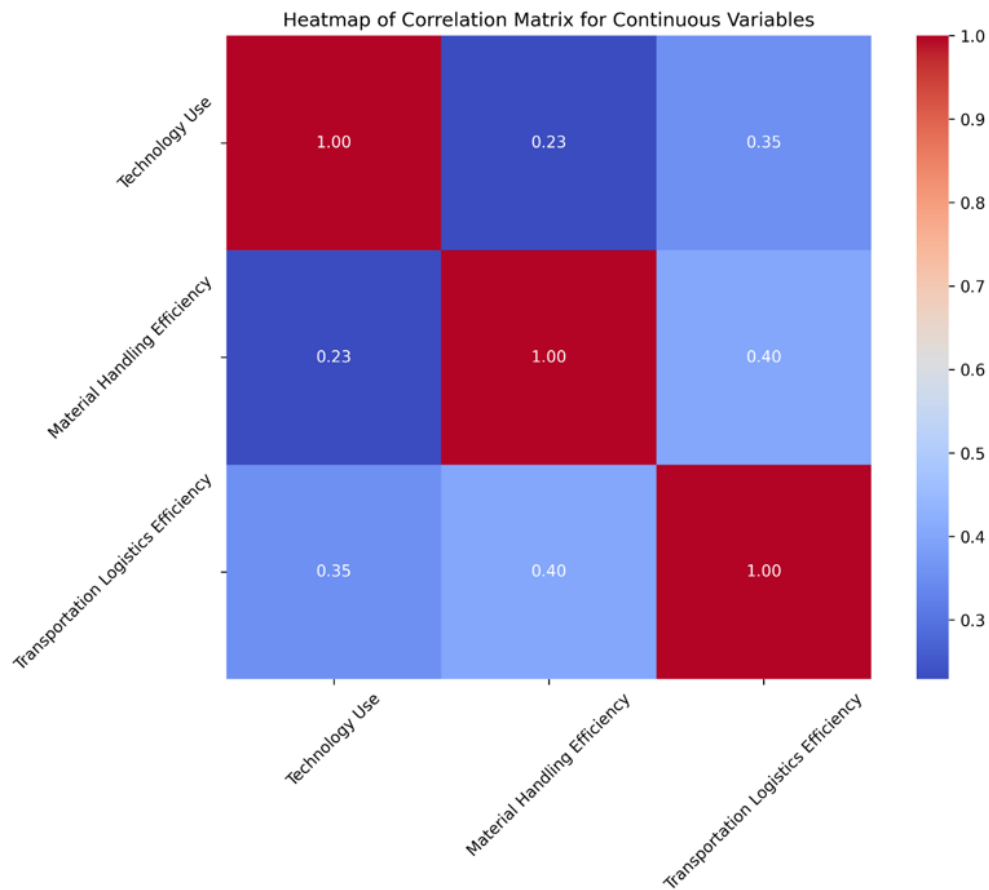


Figure 11: Heatmap of Correlation Matrix for correlated variables

The relationship between Sustainability Integration and Technological Adoption was further analyzed using Spearman's correlation. Spearman's analysis revealed a moderate positive correlation (correlation = 0.304, $p = 0.00016$), indicating that organizations with higher levels of sustainability integration are more likely to adopt advanced technologies.

In summary, the analysis highlights the critical role of technology and sustainability integration in improving logistics efficiency and coordination. Organizations that integrate sustainability practices are not only more likely to adopt advanced technologies but also benefit from improved transportation logistics and material handling processes, reducing delays and enhancing overall efficiency.

5. Results and Analysis - Qualitative Analysis

In addition to survey data, observational analysis was conducted at two construction sites in Saudi Arabia to capture real-world logistics practices and sustainability measures. The selected sites represent distinct contexts: a large-scale smart city project in NEOM (Case Study 1) and a high-density residential development in Jeddah (Case Study 2). The observations focused on three main dimensions (see Table 3), including logistics coordination, material handling, and sustainability practices, allowing for a comparative assessment of operational challenges and best practices across different project types.

Table 1: Observational Data Analysis Recorded from the selected sites in Saudi Arabia

	Case Study 1: Smart City Development	Case 2: Residential Development
Location	NEOM City	Jeddah City
Scope	A large-scale smart city development in NEOM focusing on advanced infrastructure, sustainability, and renewable energy integration. The project involves international suppliers and innovative construction techniques, creating complex logistical requirements.	A high-density residential project in urban Jeddah focused on affordable housing, with significant logistical challenges due to constrained urban spaces and ongoing city infrastructure developments.

Logistics Coordination	<ul style="list-style-type: none"> • The project demonstrated a high degree of logistics complexity, with material deliveries involving multiple international suppliers. • Coordination relied on centralized planning systems and frequent communication between stakeholders. • Delays were noted due to differences in customs regulations and inconsistencies in supplier timelines. 	<ul style="list-style-type: none"> • Material deliveries relied on conventional planning methods, such as manual scheduling and coordination through phone or email. • Frequent delays occurred due to miscommunication between subcontractors and logistics teams. • Urban restrictions, including narrow roads and limited delivery windows, exacerbated logistical challenges.
Material Handling	<ul style="list-style-type: none"> • Automated cranes and forklifts were deployed for handling heavy materials, reducing manual labor requirements. • Space utilization was efficient, with storage areas organized based on anticipated construction phases. • Challenges arose due to limited skilled personnel for managing advanced handling systems, leading to temporary inefficiencies. 	<ul style="list-style-type: none"> • Materials handling depended on manual labor and traditional equipment such as forklifts. • Space constraints required off-site storage of materials, increasing transportation time and costs. • Safety issues were noted, including inadequate training on material handling and improper stacking of heavy items.
Sustainability Practices	<ul style="list-style-type: none"> • Electric vehicles (EVs) were used for on-site logistics to minimize carbon emissions. • Waste management practices included on-site sorting and recycling, with construction debris repurposed for secondary applications. • Energy-efficient construction practices, such as prefabrication, were employed to reduce material waste and on-site emissions. 	<ul style="list-style-type: none"> • Sustainability efforts were limited, primarily involving the use of basic recycling of packaging materials. • On-site power usage was reduced through energy-efficient lighting and solar-powered tools. • High emissions from diesel-powered trucks used for deliveries highlighted the need for cleaner transportation solutions.

To conclude, the comparative observations highlight clear operational contrasts between the two case studies. Case Study 1 (NEOM) utilised digital coordination tools, automation, and integrated sustainability practices to manage complex supply chains effectively, despite challenges with cross-border logistics and specialized skill shortages. In contrast, Case Study 2 (Jeddah) relied on manual coordination and traditional handling methods, leading to frequent delays, safety risks, and limited environmental integration. These differences emphasize the importance of centralized planning systems, workforce upskilling, and cleaner transport solutions in achieving efficient and sustainable construction logistics, especially in urban residential contexts where spatial and regulatory constraints are more pronounced.

6. Discussion and Practical Implications

This section interprets the findings from both the survey and observational data to uncover the key factors influencing logistics efficiency and sustainability in Saudi Arabia’s construction sector. While the results reveal operational variation across project types and organizational practices,

they also point to common challenges, such as weak coordination, limited digital integration, and fragmented sustainability implementation. These findings are particularly relevant in the context of Vision 2030 and the national push toward smart, sustainable infrastructure development.

To deepen the analysis and structure the interpretation of results, the Technology–Organization–Environment (TOE) framework was introduced as a theoretical lens. Originally developed by Tornatzky and Fleischer (1990), the TOE framework is widely used in technology adoption research to understand how internal and external contexts shape innovation uptake. In this study, the TOE framework was applied to organize findings across three domains:

- **Technology:** infrastructure, tools, and digital capabilities affecting logistics processes.
- **Organization:** workforce skills, internal culture, and managerial readiness.
- **Environment:** external factors such as regulatory conditions, urban constraints, and sustainability imperatives.

The following sections discuss the results within each of these dimensions, highlighting their implications for Digital Twin (DT) integration and

sustainable logistics development. The sections conclude with introducing S-Twin conceptual framework (see Figure 12), which illustrates how digital twin can support long-term sustainability within construction logistics in Saudi Arabia.

Technology

The study reveals a moderate but inconsistent level of technology adoption, with only 10% of respondents reporting regular use of tools like real-time tracking and automated handling systems. This mirrors previous observations by Omrany et al. (2023), who noted significant barriers to DT implementation due to lack of standardisation and limited stakeholder capacity. The observational data supports this, particularly in Case 2 (Jeddah residential project), where logistics relied heavily on manual coordination and outdated communication methods, resulting in frequent delivery delays and misalignment between subcontractors.

Yet, statistical analysis indicates that technology plays a significant enabling role in logistics optimisation. A moderate positive correlation ($r = 0.35$) was observed between technology use and transportation efficiency, while a weaker but still notable relationship was found with material handling ($r = 0.23$). These results suggest that technology, even at a basic level of adoption, enhances key operational outcomes. The integration of DTs in Case 1 (NEOM Smart City) showcased advanced logistics planning capabilities such as automated cranes, centralised data systems, and real-time performance monitoring. These enabled reduced downtime, optimised space utilisation, and greater responsiveness, attributes closely aligned with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), particularly in reducing over-ordering, emissions, and material waste. Moreover, the potential for DTs to embed life-cycle carbon data and simulate delivery routes further supports alignment with SDG 9 (Industry, Innovation, and Infrastructure), reinforcing the call by Zhang et al. (2024) for integrated digital ecosystems in logistics.

Despite such promise, the Chi-square tests suggest no significant difference in technology adoption across company types or project typologies, reflecting a sector-wide challenge of digital fragmentation (Wu et al., 2024). Therefore, while DTs hold potential as a strategic logistics enabler (Malaibari et al., 2024), wider implementation remains constrained without coherent national-level support and capacity-building strategies.

Environment

Logistics coordination emerged as a core challenge,

with 53.3% of respondents reporting moderate difficulty and 15.3% describing it as very challenging. A strong negative correlation ($r = -0.50$) between logistics coordination and transport delays underscores the operational consequences of weak coordination mechanisms. These inefficiencies were especially evident in the residential case study, where outdated scheduling practices and poor subcontractor communication led to repeated delays and on-site congestion.

The fragmentation observed echoes findings from Janné (2020), who attributes logistical breakdowns to silos between contractors, suppliers, and local authorities. It also draws emphasis on the importance of data-driven decisions in informing supply chains, and how to account for environmental concerns (Yang et al., 2024). In Saudi Arabia, this is further compounded by the multi-layered governance structure involving ministries, gigaproject entities (e.g. ROSHN, PIF), and international consultants. While these layers aim to provide oversight, they often lack a unified logistics data infrastructure.

In contrast, Case 1 demonstrated how centralised DT environments can streamline inter-organisational logistics by integrating supply chain data with compliance records and environmental metrics. Such configurations enable municipal agencies to respond dynamically to logistics-related disruptions, supporting SDG 11 (Sustainable Cities and Communities) through improved urban resilience.

Moreover, the Chi-square test found a significant association between sustainability integration and company type ($p = 0.025$) and infrastructure projects ($p = 0.038$). These findings imply that larger or more complex projects (and organisations) are more likely to embed sustainability principles. This has implications for policy and procurement, suggesting that mandating sustainability-oriented logistics strategies, particularly on public infrastructure, could incentivise cross-sectoral coordination. This aligns with Morel et al. (2020), who advocate for collaborative governance models to overcome institutional inertia and siloed decision-making, supporting SDG 17 (Partnerships for the Goals).

Organization

While digital tools can support logistics optimisation, their effectiveness is contingent on the people who implement and manage them. The study identified labour skills, training gaps, and resistance to change as major barriers to improving both logistics and sustainability outcomes. Specifically, 88 respondents cited lack of expertise as the primary challenge to sustainable logistics

integration, surpassing cost, regulatory hurdles, and organisational resistance. The observational data revealed critical training gaps in both projects, particularly regarding material handling safety and sustainable transport planning. In the Jeddah site, improper stacking and insufficient training were linked to safety hazards, while low-tech practices like paper-based scheduling and diesel-heavy transport limited opportunities for sustainability integration. This aligns with O'Reilly and Kiyimba (2015), who argue that without meaningful skills development, digital tools remain underused. The low percentage of respondents (15.3%) reporting regular training confirms this stagnation. Furthermore, organisations that had stronger sustainability integration also showed higher likelihood of technology adoption (Spearman's $r = 0.304$, $p < 0.001$), suggesting that a sustainability mindset may be a precursor to digital maturity. In terms of SDG alignment, respondents most frequently cited support for SDG 7 (Affordable and

Clean Energy) and SDG 3 (Good Health and Well-being), though climate-focused goals like SDG 13 ranked low in both awareness and implementation. This reflects a gap between perceived value of sustainability and actual integration, as seen in the 26.7% reporting only slight sustainability integration (Tookey and Dhawan, 2026). Without workforce empowerment and organisational support, sustainability initiatives risk remaining symbolic rather than systemic. The findings underscore the need to prioritise SDG 4 (Quality Education) within construction logistics through vocational training, capacity building, and change management programmes to ensure workforce readiness and cultural alignment with digital and sustainable practices. It also shows that emphasizes the importance of monitoring data streams in technologies like digital twin, so it improves decision-making (Gehring et al., 2025).

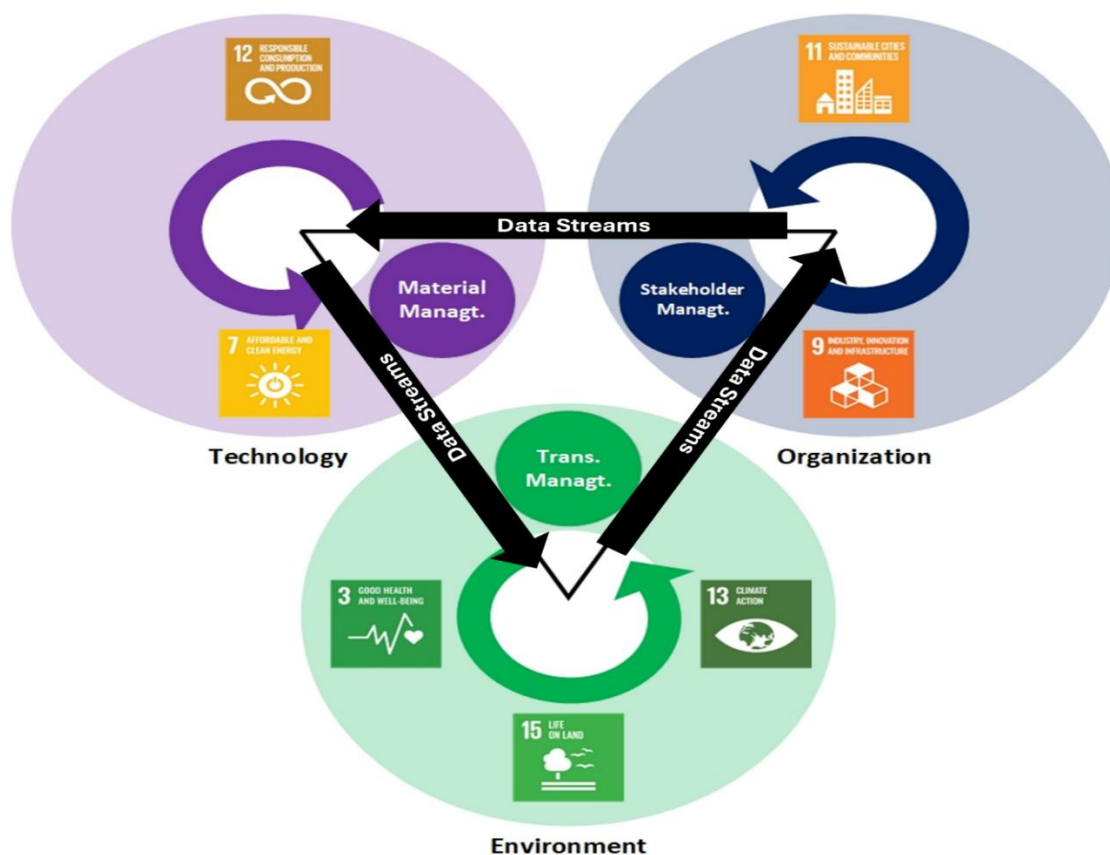


Figure 12: S-Twin Conceptual Framework Model

7. Conclusion

This study examined the integration of sustainability and advanced technologies within Saudi Arabia's construction logistics, identifying both process inefficiencies and systemic integration gaps as major challenges. While sustainability practices are increasingly recognized, limited alignment with operational processes and

fragmented supply chain coordination hinder broader adoption. Larger projects like NEOM demonstrate promising efforts in green logistics, while smaller projects face significant constraints due to budgetary and technical limitations. Digital Twin (DT) technology offers a transformative, data-driven solution to address these challenges. By enabling real-time monitoring, predictive

analytics, and resource optimization, DTs align logistics operations with Sustainable Development Goals (SDGs) such as Climate Action (SDG 13), Responsible Consumption and Production (SDG 12), and Sustainable Cities and Communities (SDG 11). Their adaptability to various project scales further underscores their potential for widespread adoption. Achieving sustainable and efficient construction logistics requires a cohesive

framework combining policy support, stakeholder collaboration, and capacity building. Investing in scalable DT solutions and incentivizing green logistics initiatives will position Saudi Arabia as a leader in sustainable construction, advancing the Vision 2030 agenda. Addressing these challenges will enable the sector to contribute to long-term economic and environmental resilience.

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