WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Usage of Digital Twin Technology for Sustainable Development in Sri Lanka's Construction Sector

Geekiyanage C.L.[a*], Prabodhani L.H.K.N.[a], Wijerathna R.M.K.K.[a], Dr. Lekamge L.S.[a], Erandi J.D.T.[b]

[a] *Department of Computing & Information Systems, Faculty of Computing, Sabaragamuwa University of Sri Lanka.*
[b] *Department of Data Science, Faculty of Computing, Sabaragamuwa University of Sri Lanka*

A B S T R A C T

Digital Twin (DT) technology is transforming the global construction industry, offering real-time monitoring, better decision-making, and enhanced project outcomes. However, DT is primarily used in the design and planning phase, with limited integration across the entire construction lifecycle. This research explored the applications, benefits, and barriers to adopting DT technology in all phases of the construction lifecycle in the Sri Lankan context. Data was collected through a two-phase survey, with Phase 1 involving 254 responses from professionals, including engineers, construction managers, architects, consultants, and site supervisors, representing 25 construction companies in Sri Lanka. This phase focused on identifying the phases where DT is applied, the benefits experienced, and the barriers hindering its broader adoption. Phase 2 included 237 responses, specifically aimed at collecting strategies to overcome DT adoption barriers. Qualitative techniques, descriptive statistics, cross-analysis, and graphical representation were used to analyze the data. The findings showed that DT is widely used in the design and planning phase, with minimal usage in the construction and operational phases and no usage observed in the end-of-life phase within Sri Lanka's construction industry. Key barriers identified include a lack of awareness about DT technology, insufficient technical expertise, organizational resistance to change, and high cost of implementation. Based on these findings, the study proposed a strategic framework consisting of 15 sub-barriers and 30 practical strategies categorized under five main themes. The framework was validated by 196 industry experts based on feasibility, clarity, and relevance. These strategies contribute to sustainable development in the construction industry by using DT technology across all phases of the construction lifecycle, specifically focusing on the Sri Lankan context.

Keywords: Adoption Barriers, Construction Lifecycle, Digital Twin Technology, Sri Lanka Construction Industry, Sustainable Development Strategies

1. Introduction

The construction sector in Sri Lanka, as in many developing countries, plays a pivotal role in driving economic growth. However, this growth often comes at the cost of environmental degradation, inefficient resource utilization, and sustainability challenges. As global awareness shifts toward sustainable development, the need for the construction industry to adopt innovative, data-driven technologies has become increasingly critical. Among the emerging technologies, Digital Twin (DT) technology stands out as a transformative solution with the potential to address many of the sector's persistent inefficiencies.

A digital twin is a virtual replica of a physical asset, system, or process that is continuously updated with real-time data. In the construction industry, DT technology integrates with systems such as Building Information Modeling (BIM) and Internet of Things (IoT) sensors to monitor, simulate, and optimize performance across the project lifecycle. This dynamic integration facilitates real-time decision-making, predictive maintenance, enhanced collaboration, and efficient resource management- all of which are essential for achieving sustainable construction practices (Cheng et al., 2024).

While global studies have demonstrated the effectiveness of DT in improving construction outcomes, particularly in safety management (Feng et al., 2021), infrastructure monitoring (Kineber et al., 2023), and prefabricated building processes (Liu, 2022), its implementation in Sri Lanka remains largely limited to the early design and planning phases. Recent research indicates that adoption across construction, operational, and end-of-life phases is minimal, with several barriers impeding its widespread use. These barriers include lack of awareness, insufficient technical expertise, resistance to change, and high implementation costs (Omrany et al., 2023).

The need to explore the current state of DT adoption within the Sri Lankan context is, therefore, both timely and critical. Existing literature highlights global trends and benefits but lacks context-specific investigations into how DT can be adapted for countries like Sri Lanka, where technological infrastructure, policy support, and skilled labor may be limited (Zhou et al., 2021). Moreover, there is a knowledge gap in understanding how DT can be utilized throughout the entire construction lifecycle within such developing economies.

This study aims to address these gaps by evaluating the current application of DT technology across different phases of the construction lifecycle in Sri Lanka. It further investigates the perceived benefits and barriers from the perspective of industry professionals and proposes practical, localized strategies to encourage broader adoption. By doing so, this research contributes valuable insights to the global discourse on digital transformation in construction, with a specific focus on sustainability and applicability in resource-constrained environments.

2. Literature Review

Digital Twin (DT) technology has emerged as a powerful enabler of digital transformation within the construction industry, offering capabilities such as real-time monitoring, predictive analytics, and enhanced lifecycle management. DT systems function by creating digital replicas of physical assets, integrating data from Building Information Modeling (BIM), Internet of Things (IoT) sensors, and various simulation tools. This enables optimized performance throughout the construction project lifecycle, with improved decision-making, proactive planning, and resource efficiency (Cheng et al., 2024; Liu, 2022).

On a global scale, DT technology is widely recognized for its ability to contribute to sustainable construction by minimizing material waste, increasing design accuracy, and improving scheduling through simulation-based planning. Several studies emphasize the role of DT in the design and planning phases, where its impact is most evident in visualization, resource forecasting, and scenario evaluation (Zhou et al., 2021). These early-stage benefits help reduce errors, avoid delays, and optimize resource allocation. Moreover, DT supports construction safety through real-time surveillance, enabling faster hazard detection and resolution on-site (Feng et al., 2021).

Technological integration plays a central role in maximizing DT's potential. DT systems often operate in tandem with technologies such as BIM, IoT, cloud computing, artificial intelligence (AI), and augmented reality. These tools work together to automate monitoring, facilitate smart scheduling, and enable real-time system feedback loops. Research confirms that the convergence of these platforms is critical for driving intelligent automation and predictive maintenance capabilities (Guo et al., 2022; Tuhaise et al., 2023). Furthermore, studies emphasize how this integration helps achieve energy optimization and environmental monitoring, which are central to green construction initiatives (Omrany et al., 2023).

Practical applications of DT are also expanding across niche domains. For example, Cheng et al. (2024) developed a DT-based platform for tunnel construction that combined real-time data collection and environmental monitoring to improve precision in underground works. Similarly, the use of DT in prefabricated building systems has enabled enhanced supply chain coordination, improved component tracking, and real-time design alterations to minimize material waste (Zhou, Wei, & Peng, 2021). These context-specific implementations highlight DT's ability to be tailored for complex or high-risk construction environments.

A significant advantage of DT technology is its support for lifecycle-based construction thinking. Rather than being limited to a project's front-end phases, DT has the potential to inform activities across the operational, maintenance, and decommissioning stages. Studies by Salem and Dragomir (2022) demonstrated that DT can extend asset longevity by allowing for predictive maintenance and operational performance analytics. Such applications enable data-informed interventions, which improve user safety, reduce energy consumption, and minimize operational disruptions. However, the full lifecycle integration of DT remains underdeveloped in most contexts.

While DT's effectiveness is well-documented in the early phases of construction, its integration across the entire project lifecycle remains limited. Most existing implementations are concentrated in design and planning, while real-time DT use in construction execution, facilities management, and decommissioning is still rare (Su et al., 2023; Zhou et al., 2021). This narrow scope restricts DT's full value proposition, particularly in applications that support long-term performance tracking, adaptive reuse, or sustainable demolition planning.

A further issue is the geographic bias in current DT research. The majority of empirical studies and case implementations originate from developed economies such as the United States, the United Kingdom, China, and Western Europe. These regions benefit from robust digital infrastructure, supportive government policies, and a high level of technological literacy (Opoku et al., 2022; Omrany et al., 2023). As a result, the findings may not be fully applicable to regions with limited infrastructure, financial constraints, or fragmented construction markets.

3. Research Objectives

The central aim of this study is to investigate the current use of Digital Twin (DT) technology across the construction lifecycle in Sri Lanka and to explore how its broader adoption can contribute to sustainable development. Although DT has demonstrated significant benefits in global contexts, its application within developing countries like Sri Lanka remains limited, particularly beyond the design and planning phases. This research seeks to address this gap by identifying existing usage patterns, evaluating perceived benefits and barriers, and developing a practical, expert-validated framework to guide the adoption of DT technology across the entire construction lifecycle.

Primary Objective: To investigate the implementation and impact of DT technology across the entire lifecycle of construction projects in Sri Lanka and propose a validated framework of practical strategies to overcome barriers to its adoption.

Secondary Objectives

- **RO1**: To analyze the current utilization of digital twin technology in different phases of the construction lifecycle in Sri Lanka.
- **RO2**: To evaluate the key benefits of digital twin technology in enhancing project outcomes within the Sri Lankan construction industry.
- **RO3**: To identify and analyze the major barriers to the widespread adoption of digital twin technology across the construction lifecycle in Sri Lanka.
- **RO4**: To propose a validated framework of practical strategies that can be used to overcome identified barriers and promote DT technology adoption across all phases of the construction lifecycle.

4. Methodology

The study employed a two-phase mixed-methods research design to explore the usage of DT technology in Sri Lanka's construction industry. The process was divided into two connected phases: the first focused on identifying the current state of DT adoption, benefits and associated barriers, and the second aimed to collect strategies to overcome those barriers.

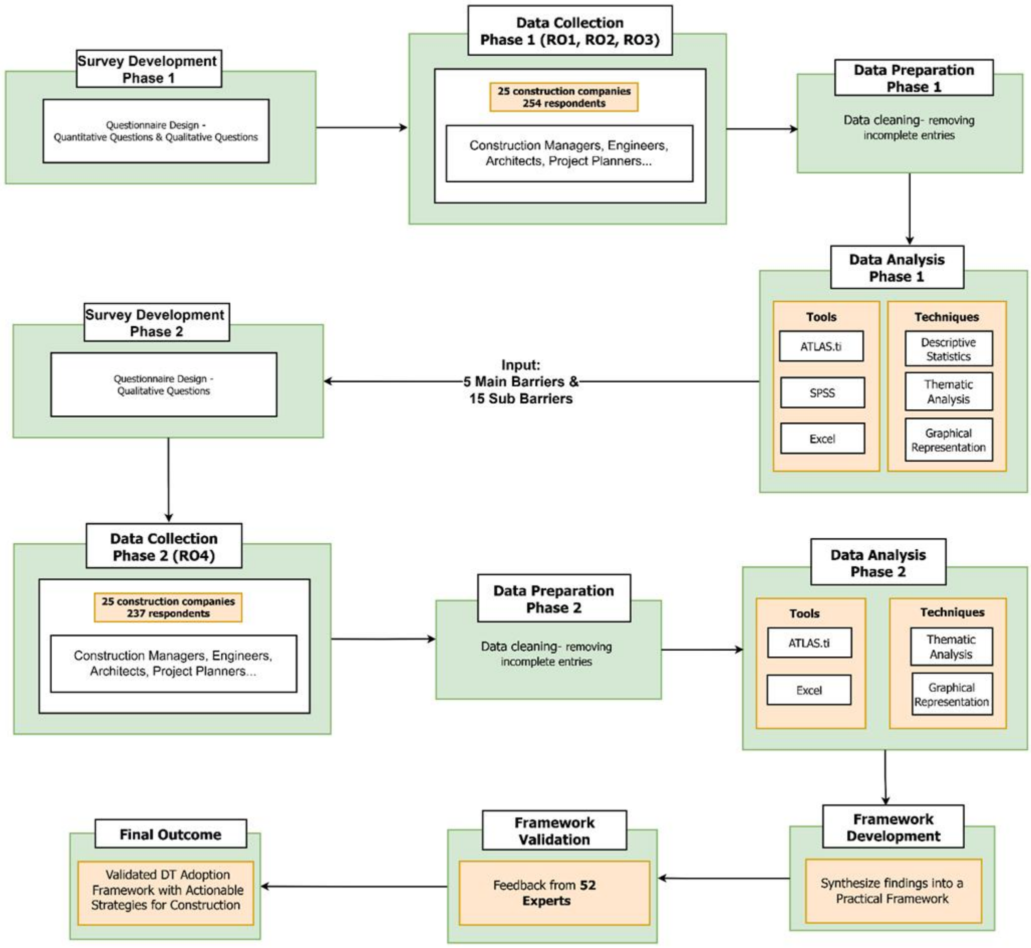

Fig. 1 - Methodology

4.1 Survey Development – Phase 1

The first phase began with developing a structured questionnaire containing quantitative and qualitative questions. The aim was to explore the level of DT adoption across various construction lifecycle stages, the perceived benefits, and the barriers limiting widespread implementation.

4.2 Data Collection – Phase 1 (RO1, RO2, RO3)

Data for RO1, RO2, and RO3 were collected using a single structured questionnaire containing both quantitative and qualitative questions. The questionnaire was distributed among professionals from 25 construction companies, and 254 valid responses were obtained. Respondents included construction managers, engineers, architects, consultants, and project planners, all actively involved in various phases of construction projects.

- For **RO1**, which focused on identifying the level of DT adoption across the construction lifecycle, respondents were asked to indicate the specific phases in which DT was applied. These phases included design and planning, construction, operation and maintenance, and end-of-life or decommissioning.
- To address **RO2**, which explored the benefits and impacts of DT in construction projects, the questionnaire included a section where participants selected the benefits they had experienced through DT use. They were also asked to rate the perceived impact of DT on project success factors such as cost, efficiency, safety, resource use, collaboration, and maintenance. These ratings were given on a five-point Likert scale ranging from very low to very high, enabling the analysis of how DT contributes to project performance.
- For **RO3**, which aimed to identify the barriers to DT adoption, open-ended questions were included. Respondents were asked to list any challenges or obstacles they had faced in implementing DT within their projects or organizations.

4.3 Data Preparation – Phase 1

Collected data were reviewed for completeness. Incomplete or invalid entries were removed, ensuring only usable and clean data were included in the analysis.

4.4 Data Analysis – Phase 1

The cleaned dataset collected in Phase 1 was analyzed using a combination of quantitative and qualitative techniques, depending on the nature of each research objective. The analysis was conducted using ATLAS.ti, SPSS, and Excel.

- **RO1:** To analyze responses related to RO1, descriptive statistics were used in SPSS and Excel. The frequency of DT adoption was calculated across four phases of the construction lifecycle: Design and Planning, Construction, Operation and Maintenance, and End-of-Life/Decommissioning.

The results were visualized using bar charts and pie charts to illustrate which phases had higher or lower adoption rates, enabling a clear comparison across lifecycle stages.

- **RO2:** Data for RO2 were analyzed using descriptive analysis techniques. Participants' selections of DT benefits were quantified, and frequency counts were used to identify the most commonly cited advantages.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- $f(x)$: Probability density (y-axis value)
- μ: Mean (average rating)
- σ: Standard deviation
- x: Rating value (1 to 5)

In addition, Likert-scale responses (1 = Very Low, 5 = Very High) were statistically analyzed to evaluate the perceived impact of DT on key project outcomes such as cost, efficiency, and safety. To better understand the variability in responses, a probability density distribution of each benefit rating was created. The variability in perception was further modeled using the Normal Distribution (Gaussian) formula.

This method allowed us to visualize how tightly or widely the expert ratings were spread around the average. The resulting bell-shaped curves helped identify which benefits showed stronger agreement among respondents and which had more diverse opinions.

- **RO3:** Open-ended responses to the barrier identification question were analyzed using thematic analysis with the help of ATLAS.ti. Through systematic coding, **15 distinct sub-barriers** were extracted from the qualitative data. These sub-barriers were then grouped into **5 main barrier categories** based on conceptual similarity.

4.5 Survey Development – Phase 2

Based on the five barrier categories and fifteen sub-barriers identified in Phase 1, a second, qualitative-only questionnaire was developed to collect expert opinions on overcoming each barrier. The survey was designed to gather practical, experience-based strategies.

4.6 Data Collection – Phase 2 (RO4)

The second questionnaire was distributed to the same pool of professionals across the 25 companies. This phase gathered 237 responses, with participants suggesting strategies for each identified sub-barrier based on their operational experience.

4.7 Data Preparation – Phase 2

Similar to the first phase, the responses were reviewed, and incomplete entries were removed to ensure consistency and accuracy in the analysis.

4.8 Data Analysis – Phase 2

The collected strategy suggestions were analyzed thematically using ATLAS.ti. The most frequently suggested strategies were identified through a coding and frequency-count process.

- **Tools**: ATLAS.ti, Excel
- **Techniques**:
    - Thematic analysis (to group similar strategies)
    - Graphical representation (to identify top strategies per sub-barrier)

From each sub-barrier, the **two most frequently mentioned strategies** were selected and used in building the proposed DT adoption framework.

4.9 Framework Development

The results from both phases were synthesized into a Strategic Framework for DT Adoption. The framework included five main categories of barriers, each with three sub-barriers and two prioritized strategies per sub-barrier, resulting in a targeted and practical solution set.

4.10 Framework Validation

To ensure the framework's reliability and practical value, it was validated by a panel of **196 industry experts** who had participated in earlier phases. Experts reviewed the framework in both visual and tabular formats and evaluated it based on the following:

- **Feasibility** for implementation in local contexts
- **Clarity** and ease of understanding
- **Relevance** to operational challenges

Each criterion was rated on a **5-point Likert scale**. The results were analyzed, and **bell curves** were used to visualize the frequency distributions of the responses. The curves showed strong clustering around ratings 4 and 5, indicating high confidence and agreement across all three criteria.

4.11 Final Outcome

The final output of the study is a validated DT Adoption Framework. This framework offers practical strategies tailored to the Sri Lankan context. It serves as a guide for promoting sustainable development through the use of DT technology across the entire construction lifecycle.

5. Results and Discussion

5.1 Current Utilization of Digital Twin Technology Across the Construction Lifecycle (RO1)

The survey results revealed a significant imbalance in the adoption of DT technology across the construction lifecycle in Sri Lanka. While some phases demonstrate moderate engagement, others are entirely neglected.

As illustrated in **Fig. 2**, DT is predominantly used during the Design and Planning phase, with 48% of respondents indicating its application here.

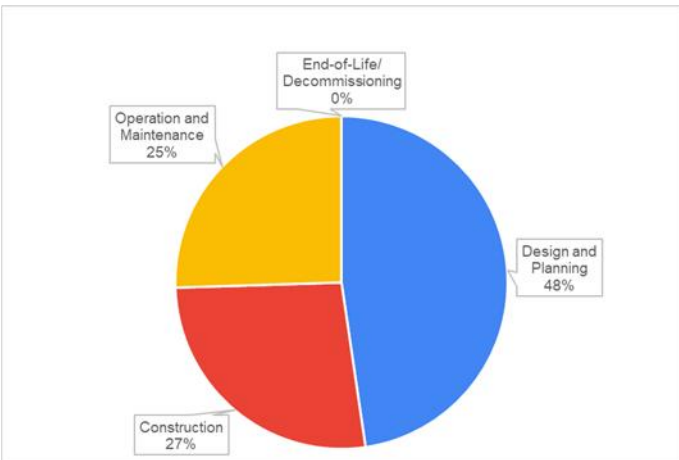

Fig. 2 - DT Adoption Across Construction Lifecycle Phases

The Construction phase follows with 27%, where DT tools are used for tracking progress, managing logistics, or improving safety. The Operation and Maintenance phase registers a usage rate of 25%, indicating relatively limited adoption despite its strong potential for optimizing building performance, predictive maintenance, and energy management. Alarmingly, 0% of respondents indicated DT usage in the End-of-Life or Decommissioning phase, exposing a critical gap in applying DT for demolition planning, material recovery, and sustainable closure of built assets.

Fig. 3 further strengthens this observation by showing not only the number of responses per phase but also the mean frequency of usage, which was rated on a scale from 1 (Never) to 5 (Always). The mean frequency trend clearly shows a downward slope across the phases, confirming the progressively declining engagement with DT beyond the early stages.

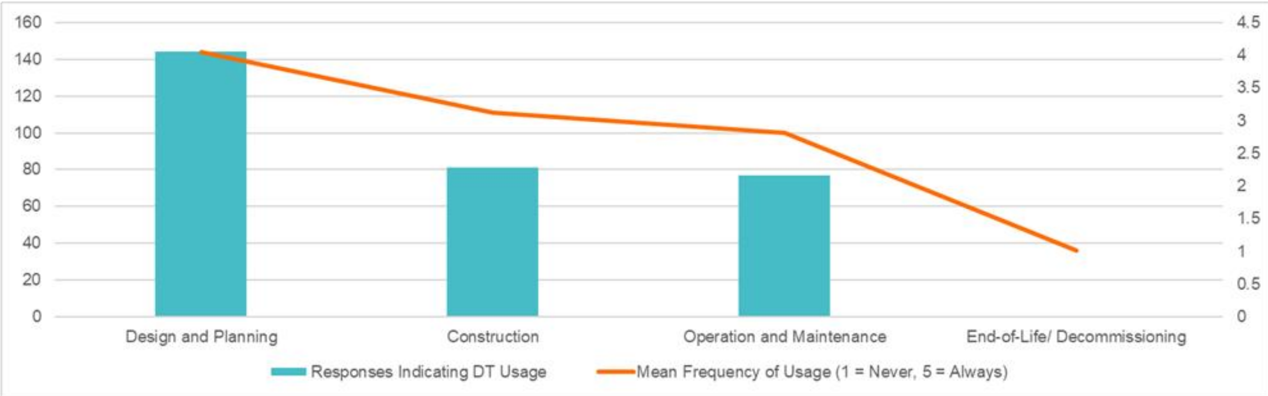

Fig. 3 - Number of Responses vs. Mean Frequency of DT Usage Across Lifecycle Phases

These results suggest that in Sri Lanka, DT is currently perceived more as a planning support tool than a long-term lifecycle enabler. This underutilization restricts its potential for promoting sustainability, operational efficiency, and informed decision-making throughout the building's lifespan.

5.2 Key Benefits of Digital Twin Technology in Improving Project Outcomes (RO2)

Fig. 4 presents the frequency of responses citing different DT-related benefits. The most cited benefit was improved project outcomes (130 responses), followed closely by cost savings (124) and better resource management (105). Enhanced safety (71), improved decision-making (79), and enhanced stakeholder collaboration (64) were also significant, while predictive maintenance was cited by 35 respondents.

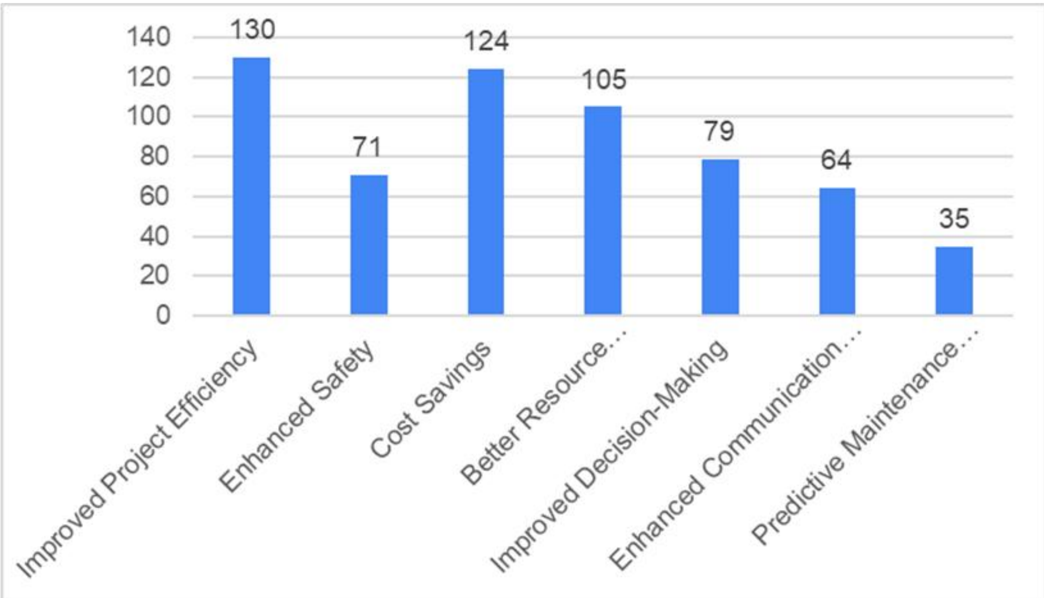

Fig. 4 - Frequency of Responses Indicating DT Benefits

To further understand the prominence of these benefits, **Fig. 5** shows a Pareto chart to show that the top three benefits- improved outcomes, cost savings, and better resource usage- account for more than 70% of total responses. This emphasizes that respondents see DT as a means to optimize overall project execution.

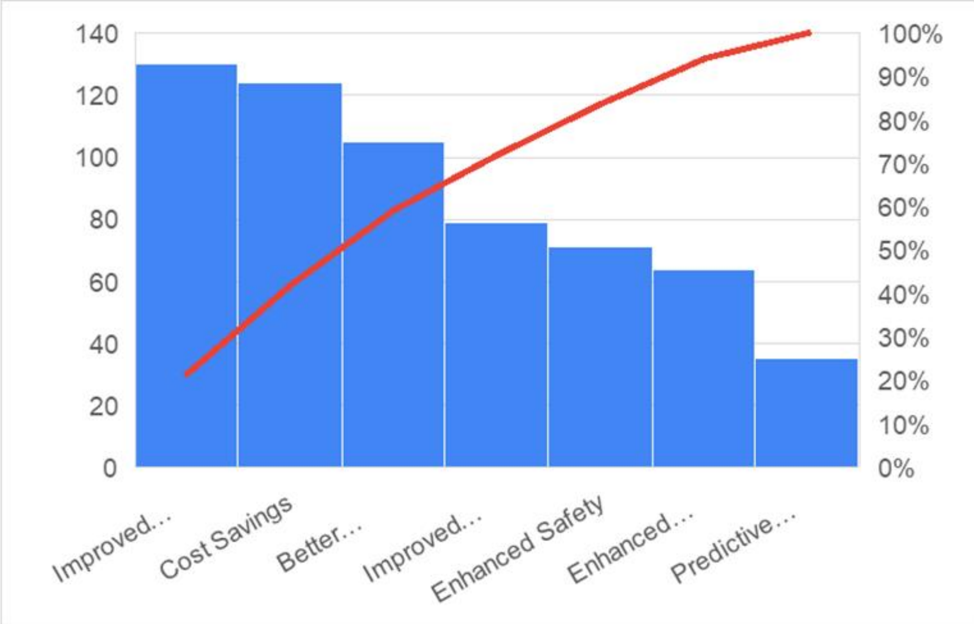

Fig. 5 - Pareto Analysis of Perceived DT Benefits

As seen in **Fig. 6**, the areas with the highest ratings were project efficiency and predictive maintenance, both scoring above 3.6 mean. Safety, cost savings, and decision-making followed closely, suggesting a generally positive outlook toward DT's value across critical project dimensions. Communication, collaboration, and resource management received slightly lower average ratings but were were still above the neutral midpoint.

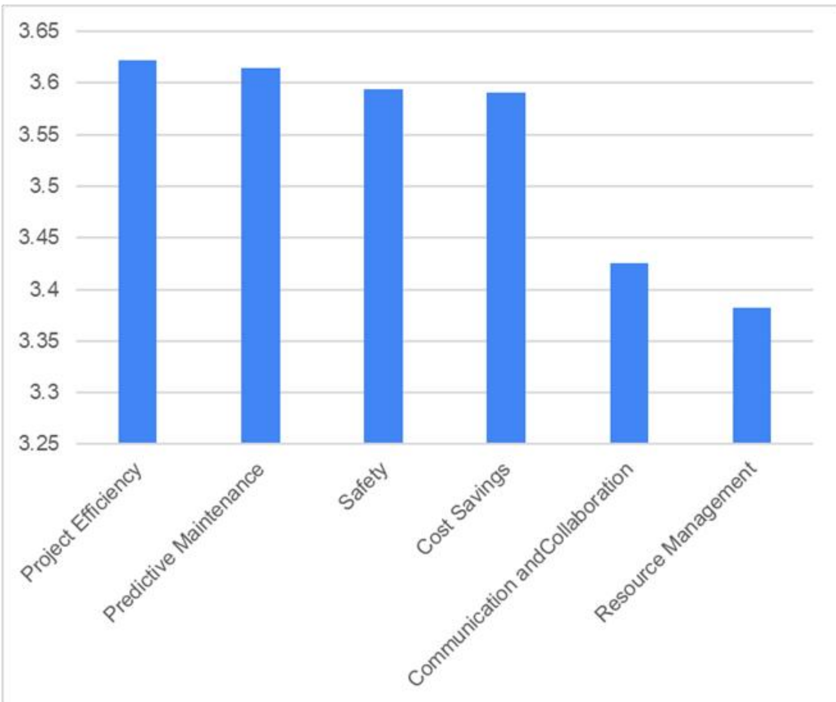

Fig. 6 - Mean Impact Ratings of DT on Project Outcomes

Finally, **Fig. 7** illustrates the probability distribution of impact ratings for each benefit category using a probability density chart. Most benefits show a consistent skew towards higher ratings (between 3 and 5), reinforcing the widespread perception that DT positively influences various project outcomes.

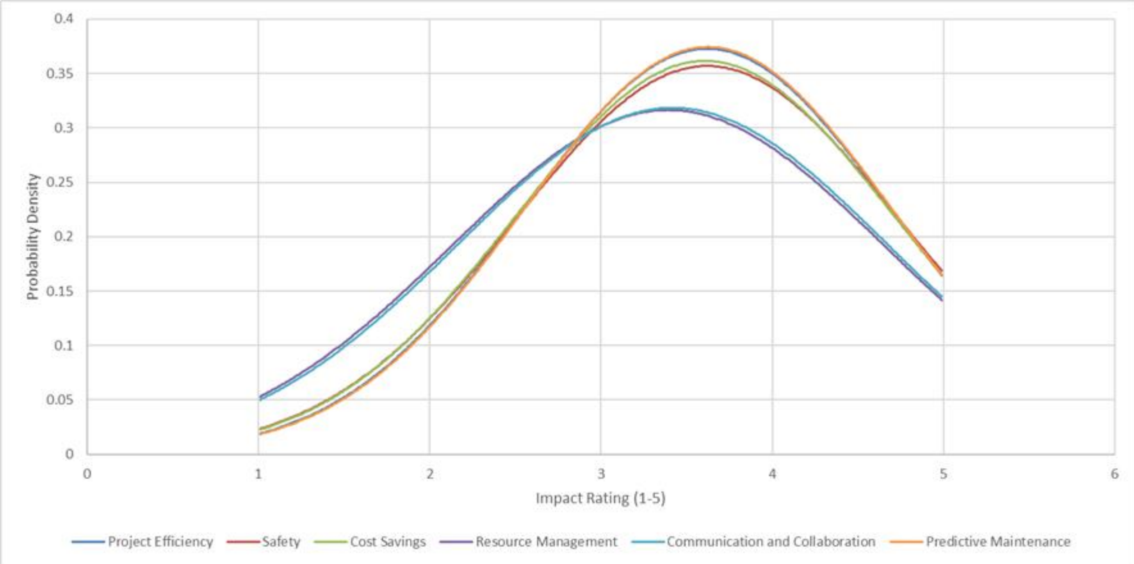

Fig. 7 - Probability Density Distribution of DT Impact Ratings

Overall, the analysis confirms that DT is valued not only for its technical capabilities but also for its broader contributions to project success. The strong ratings for project efficiency, predictive maintenance, and cost-effectiveness indicate that DT is perceived as a strategic enabler of sustainability and productivity in construction.

5.3 Barriers to Adopting Digital Twin Technology Across the Construction Lifecycle (RO3)

Through thematic analysis of these responses, 15 distinct sub-barriers were identified and grouped under five major categories. These are summarized in Table 1 and visually presented in **Fig. 8**.

Table 1 - Categorized Barriers to Digital Twin Adoption in Sri Lanka's Construction Sector

Main Barrier Category	Sub-Themes	Frequency
High Cost of Implementation	Cost of DT Software and Licensing	20
	Hardware and Sensor Investment	15
	Cost of Skilled Labor and Training	29
Lack of Technical Expertise	Lack of On-Site DT Knowledge	32
	Difficulty Understanding Software Tools	25
	Poor Collaboration Between Technical and Site Teams	26
Resistance to Change	Management Reluctance	21
	Field Team Hesitation	19
	Fear of Job Displacement	28
Inadequate Infrastructure	Weak Internet or Cloud Connectivity on Sites	17
	Lack of Integrated Platforms	15
	No IoT/Smart Tech for Data Collection	20
Limited Awareness of DT Benefits	Misunderstanding DT is Only for Design-Phase	31
	Lack of Local Examples	29
	Weak Engagement from Industry Bodies	35

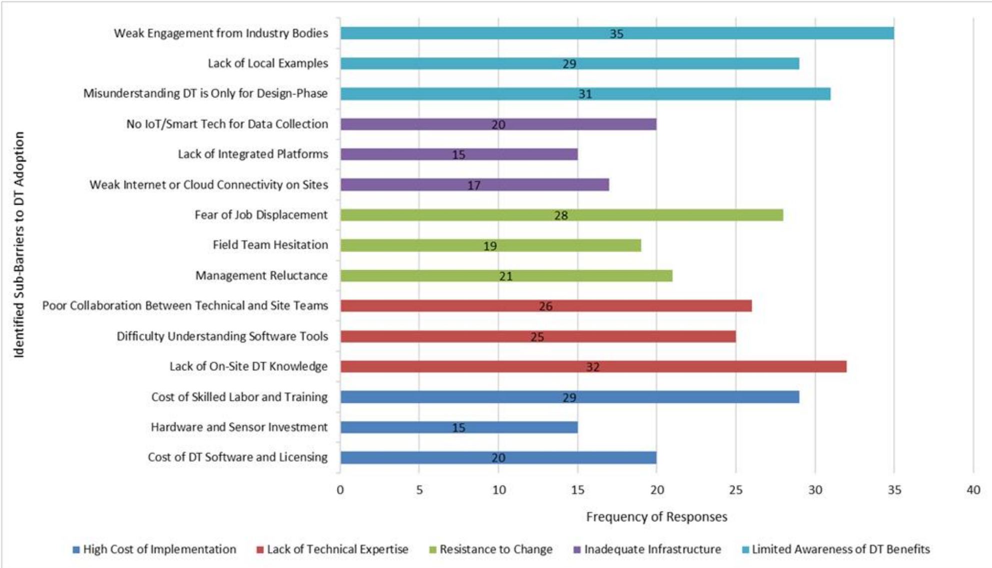

Fig. 8 - Frequency of Identified Sub-Barriers to DT Adoption by Main Barrier Category

1. **High Cost of Implementation (64 responses):** This category focuses on the financial challenges of using DT. Many participants said the cost of software and licensing is too high. Others pointed out that buying sensors and devices is expensive, and training staff or hiring skilled professionals adds to the cost. For smaller companies, these expenses can be a major obstacle to getting started with DT.

2. **Lack of Technical Expertise (83 responses):** The most commonly reported issue was the lack of technical knowledge. Respondents noted that many workers don't know how DT works or how to use the software tools. There were also problems with collaboration between digital experts and site teams, leading to poor communication and underuse of the technology.

3. **Resistance to Change (68 responses):** Change is often difficult, and this was also true for DT adoption. Some managers were reluctant to try something new, while field workers were hesitant or didn't see the need for DT. A number of participants also mentioned a fear of job loss, as they felt DT could replace certain roles or make workers feel monitored.

4. **Inadequate Infrastructure (52 responses):** Many construction sites in Sri Lanka do not have strong internet or cloud systems, making real-time DT updates difficult. Some also lack integrated digital platforms or smart devices (like IoT sensors) to collect and use data. Without this basic infrastructure, running a DT system smoothly is hard.

5. **Limited Awareness of DT Benefits (95 responses):** This was the most mentioned barrier. A large number of respondents thought DT was only useful in the design phase and didn't know it could help during construction, operations, and even demolition. Others said there are few local examples of successful DT use and that industry groups aren't doing enough to promote awareness or provide support.

These findings show that the barriers to DT adoption are not just technical or financial. They also involve people's mindsets, lack of awareness, and weak digital infrastructure. Overcoming these issues will be key to using DT more effectively and supporting sustainable construction in Sri Lanka.

5.4 Proposed Framework to Overcome Barriers to Digital Twin Adoption (RO4) Strategy Selection Through Thematic Analysis

The following figures present the results of the thematic analysis for strategy selection:

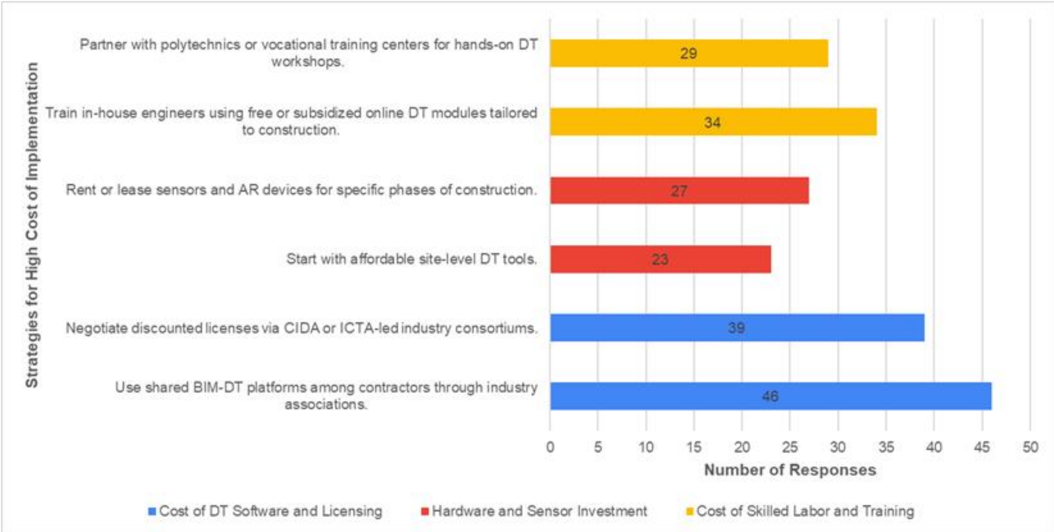

Fig. 9 - Top Two Selected Strategies to Overcome High Cost of Implementation

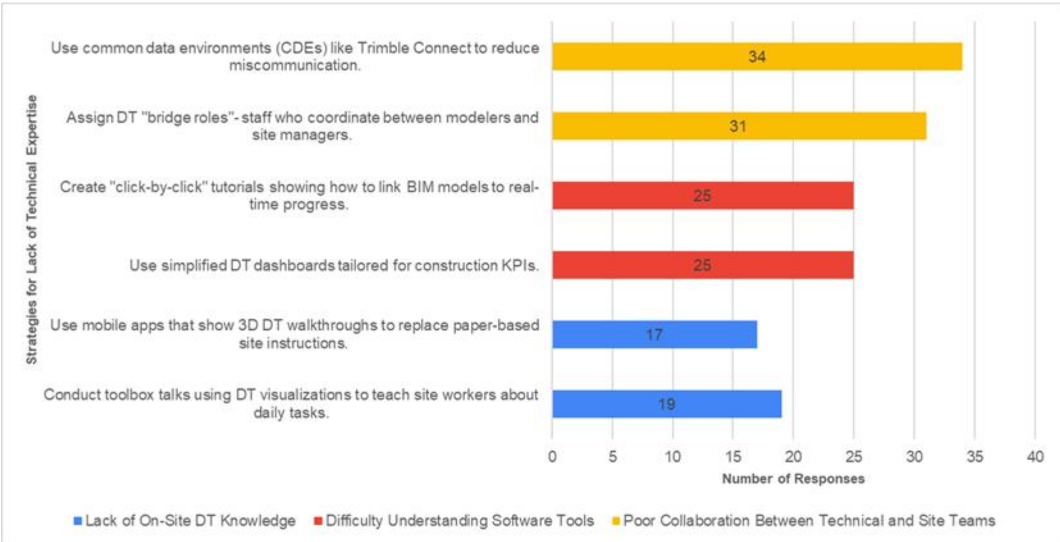

Fig. 10 - Top Two Selected Strategies to Overcome Lack of Technical Expertise

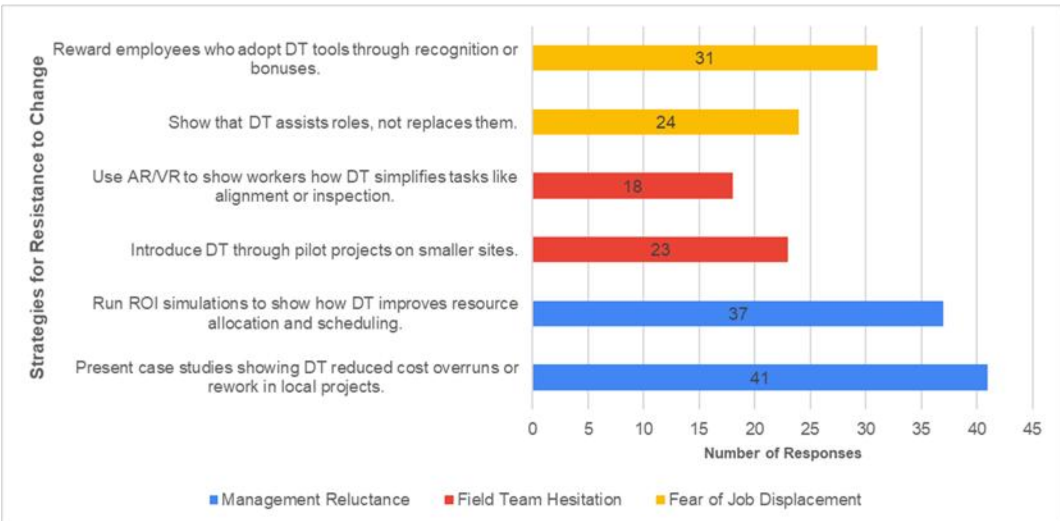

Fig. 11 - Top Two Selected Strategies to Overcome Resistance to Change

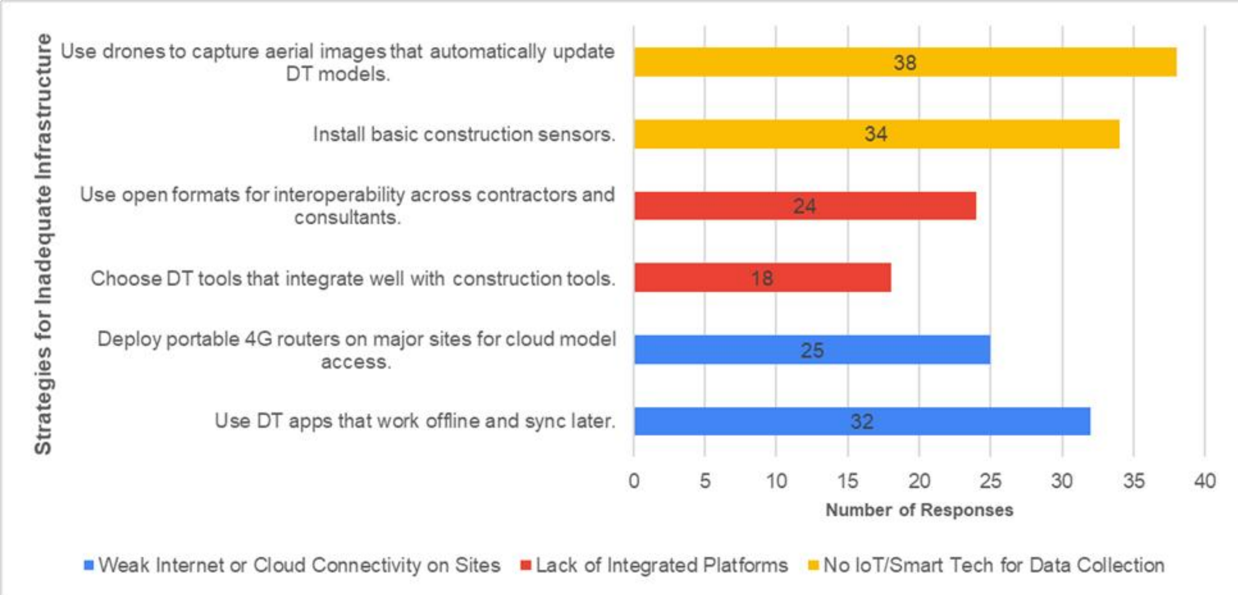

Fig. 12 - Top Two Selected Strategies to Overcome Inadequate Infrastructure

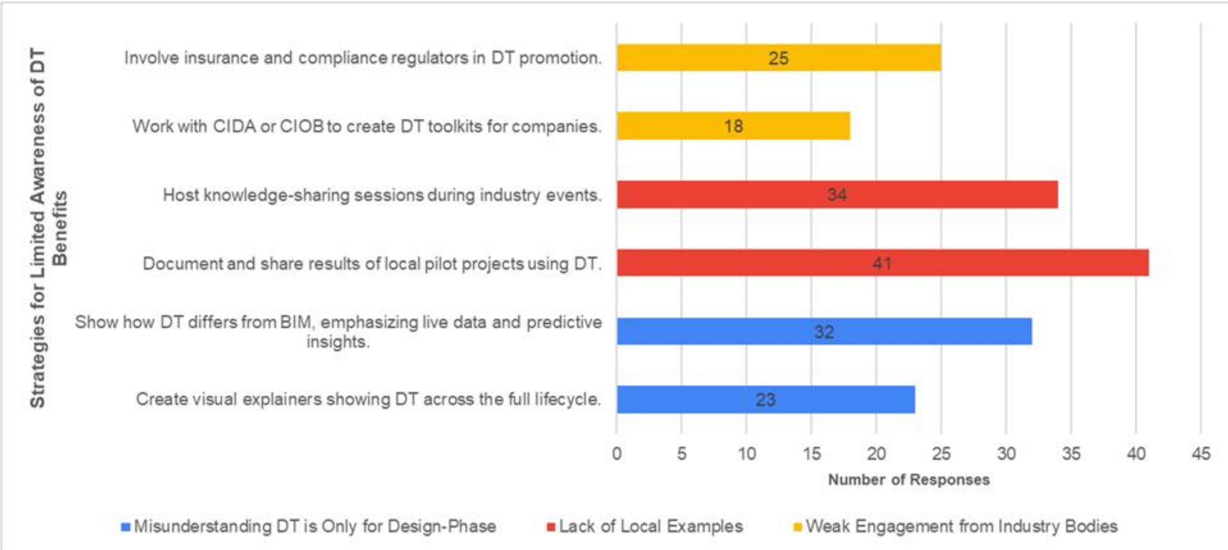

Fig. 13 - Top Two Selected Strategies to Overcome Limited Awareness of DT

5.4.1 Final Framework Presentation

The following strategic framework is organized by the five main barrier categories, with each column presenting two validated strategies for every identified sub-barrier.

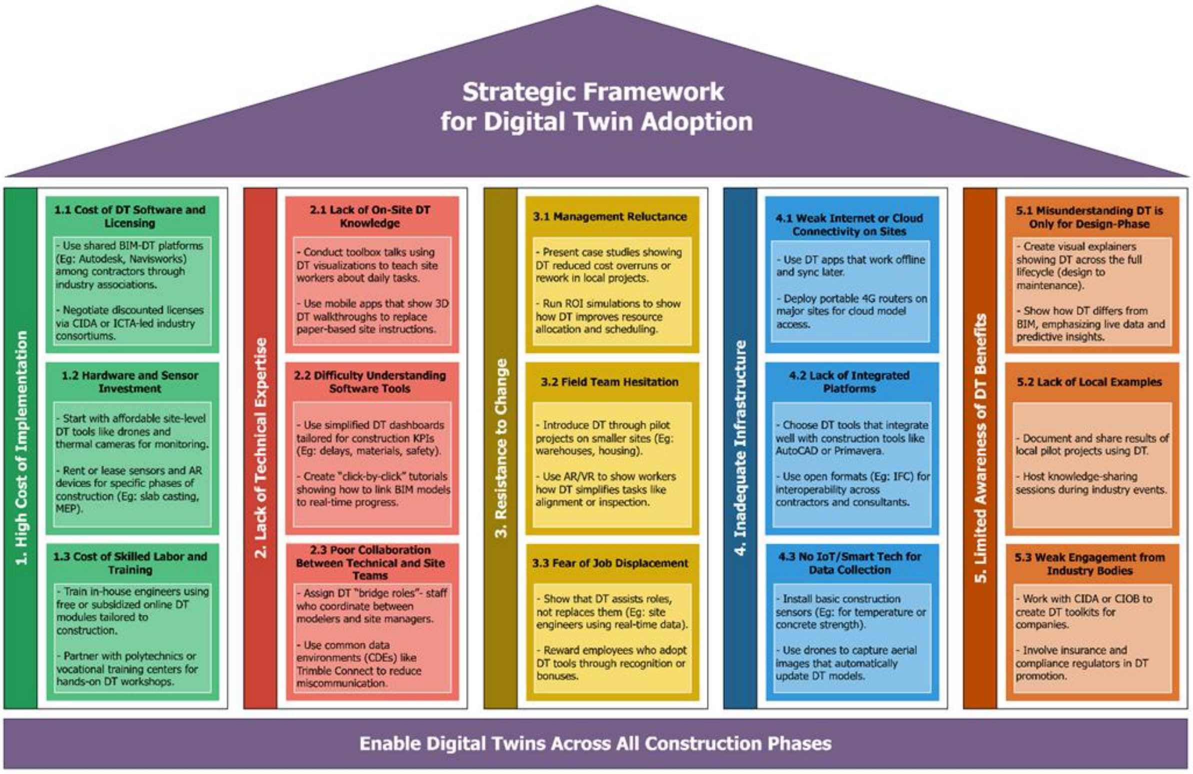

Fig. 14 – Strategic Framework for Digital Twin Adoption

5.4.2 Framework Validation

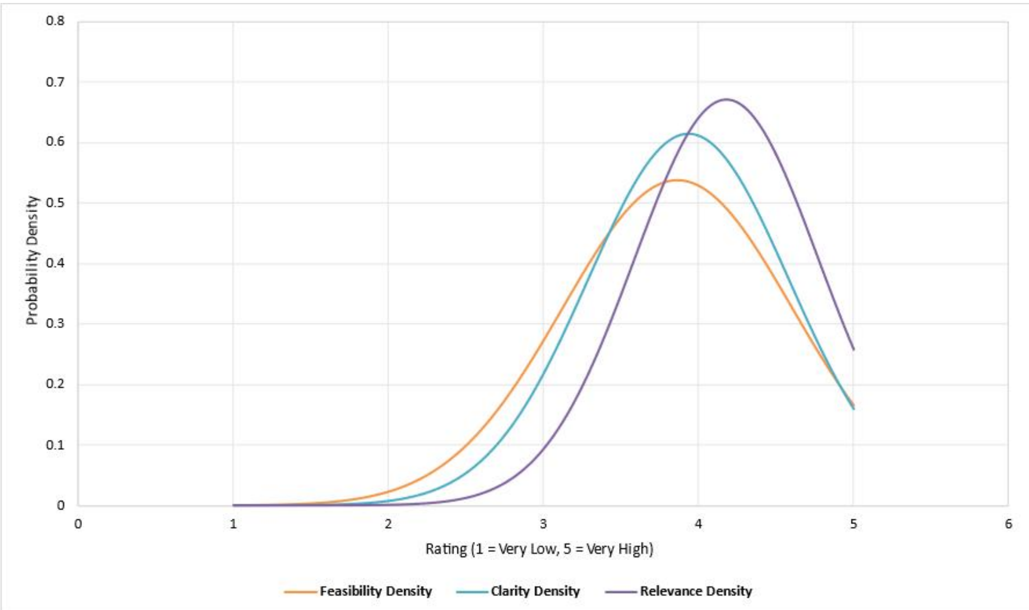

Fig. 15 – Bell Curve Distribution of Expert Ratings for Framework Validation

This graph shows the distribution of expert ratings across the three evaluation criteria. The bell curves for feasibility, clarity, and relevance all show strong clustering near ratings 4 and 5, indicating high consensus and confidence.

The bell curves reflect a normal distribution with a clear peak in the higher rating range. All three curves, representing feasibility, clarity, and relevance, demonstrate a strong central tendency toward the upper end of the scale. This indicates that most experts consistently perceived the framework as highly practical, easy to understand, and aligned with real project needs.

The bell curve analysis confirmed a high level of agreement among professionals across various companies and roles. Ratings for all three criteria were concentrated around "High" (4) and "Very High" (5) levels, with minimal variation or lower scores.

This result validates the framework as follows:

- Feasible for implementation in real construction environments
- Clear and easy to communicate across teams and organizations
- Highly relevant to operational and technological challenges faced by the industry

The outcome of this validation process is a reliable and expert-endorsed Digital Twin adoption framework built on field-tested insights and strong professional support. It provides a practical foundation for construction firms, industry bodies, and decision-makers to drive DT adoption across all phases of the construction lifecycle in Sri Lanka.

6. Conclusion

This study investigated the current adoption, benefits, and barriers of DT technology in Sri Lanka's construction industry, highlighting its limited use beyond the design and planning phase. Through a two-phase survey involving 254 and 237 participants, respectively, the research identified key barriers and collected expert-driven strategies to promote broader DT adoption. The validated framework presented in this study offers practical, industry-backed solutions to promote DT integration and serve as a roadmap for digital transformation in Sri Lanka's construction sector.

6.1 Limitations and Future Research

While this study provides valuable insights into DT adoption in Sri Lanka, several limitations should be acknowledged. The research was based on responses from professionals within 25 construction companies, which may not fully capture the views of all industry stakeholders across the country. The strategy validation process, though comprehensive, relied on expert opinion without field testing or long-term implementation data. Future research could focus on piloting the proposed framework in live construction projects to evaluate real-world effectiveness. Comparative studies across regions or countries with similar economic profiles could also help refine the framework for broader applicability.

References

1. Cheng, W., Pan, Y., Ma, Z., Cai, Y., Li, Y., & Peng, T. (2024). Tunnel Construction Site Monitoring and Digital Twin System. https://doi.org/10.23919/icact60172.2024.10471763
2. Feng, H., Chen, Q., & Soto, B. G. de. (2021). Application of digital twin technologies in construction: an overview of opportunities and challenges. ISARC Proceedings, 979–986. https://www.iaarc.org/publications/2021_proceedings_of_the_38th_ isarc/application _of _digital_twin_technologies_in_construction-an_overview_of_opportunities_and_challenges.html
3. Guo, Y., Liu, Y., Chen, J., Zheng, Y., Zhu, J., & Ji, H. (2022). Application of a New Digital Twin Model in Infrastructure Construction. https://doi.org/10.1109/ispcem57418.2022.00008
4. Kineber, A. F., Singh, A. K., Fazeli, A., Mohandes, S. R., Cheung, C., Arashpour, M., Ejohwomu, O., & Zayed, T. (2023). Modelling the relationship between digital twins implementation barriers and sustainability pillars: Insights from building and construction sector. Sustainable Cities and Society, 99, 104930. https://doi.org/10.1016/j.scs.2023.104930
5. Liu, Y. (2022). Research on the Design of Digital Twin System for Construction Safety. https://doi.org/10.1109/ispcem57418.2022.00057
6. Liu, Y., Xu, F., Yang, Z., Yan, D., & Wang, X. (2023). Research on the Application of Digital Twin in Bridge Rotation Construction. https://doi.org/10.1109/iccnea60107.2023.00094
7. Naderi, H., & Shojaei, A. (2022). Civil Infrastructure Digital Twins: Multi-Level Knowledge Map, Research Gaps, and Future Directions. IEEE Access, 10, 122022–122037. https://doi.org/10.1109/access.2022.3223557
8. Omrany, H., Al-Obaidi, K. M., Husain, A., & Ghaffarianhoseini, A. (2023). Digital Twins in the Construction Industry: A Comprehensive Review of Current Implementations, Enabling Technologies, and Future Directions. Sustainability, 15(14), 10908.
9. Opoku, D.-G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Famakinwa, T., & Bamdad, K. (2022). Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review. Buildings, 12(2), 113. https://doi.org/10.3390/buildings12020113
10. Ryzhakova, G., Malykhina, O., Pokolenko, V., Rubtsova, O., Homenko, O., Nesterenko, I., & Honcharenko, T. (2022). Construction Project Management with Digital Twin Information System. International Journal of Emerging Technology and Advanced Engineering, 12(10), 19–28. https://doi.org/10.46338/ijetae1022_03
11. Salem, T., & Dragomir, M. (2022). Options for and Challenges of Employing Digital Twins in Construction Management. Applied Sciences, 12(6), 2928. https://doi.org/10.3390/app12062928
12. Torres, J., San-Mateos, R., Lasarte, N., Mediavilla, A., Maialen Sagarna, & Iñigo León. (2024). Building Digital Twins to Overcome Digitalization Barriers for Automating Construction Site Management. Buildings, 14(7), 2238–2238. https://doi.org/10.3390/buildings14072238

13. Valerian Vanessa Tuhaise, Handibry, J., & Fonbeyin Henry Abanda. (2023). Technologies for Digital Twin Applications in Construction. Automation in Construction, 152, 104931–104931. https://doi.org/10.1016/j.autcon.2023.104931

14. Zhou, L., An, C., Shi, J., Zhengyu Lv, & Liang, H. (2021). Design and Construction Integration Technology Based on Digital Twin. https://doi.org/10.1109/psgec51302.2021.9541682

15. Zhou, Y., Wei, X., & Peng, Y. (2021). The Modelling of Digital Twins Technology in the Construction Process of Prefabricated Buildings. Advances in Civil Engineering, 2021, 1–11. https://doi.org/10.1155/2021/2801557

16. Su, S., Zhong, R. Y., Jiang, Y., Song, J., Fu, Y., & Cao, H. (2023). Digital twin and its potential applications in construction industry: State-of-art review and a conceptual framework. Advanced Engineering Informatics, 57, 102030. https://doi.org/10.1016/j.aei.2023.10203