Fernando M.K.L.I.C., Lingasabeshan, V. and Wimalaratne, P.L.I., 2025. Barriers to adopting digital twin technology for contract administration in Sri Lankan construction sector. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (eds). *Proceedings of the 13th World Construction Symposium*, 15-16 August 2025, Sri Lanka. pp. 256-272. DOI: https://doi.org/10.31705/WCS.2025.20. Available from: https://ciobwcs.com/papers/

BARRIERS TO ADOPTING DIGITAL TWIN TECHNOLOGY FOR CONTRACT ADMINISTRATION IN SRI LANKAN CONSTRUCTION SECTOR

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ABSTRACT

The construction industry in Sri Lanka faces growing pressure to improve sustainability, efficiency, and transparency across project lifecycles. Digital Twin Technologies (DTT) offer real-time, data-driven digital representations of construction processes, opening an avenue for enhancing contract administration practices and supporting sustainable construction. However, the implementation of DTT remains limited within the Sri Lankan context. This study investigates the organisational and technological barriers hindering the adoption of DTT for contract administration in Sri Lanka's construction sector. A qualitative research design was employed, incorporating a thematic analysis of semi-structured in-depth interviews with industry professionals. The findings reveal that key organisational barriers include resistance from organisational culture, generational divide, and skills shortages. The key technological challenges encompass cybersecurity risks, interoperability issues, infrastructure gaps, and data quality issues. Despite these constraints, the study identifies actionable insights to support DTT adoption, including variation management programs and pilot projects, Mentorship programs and hybrid workflows, university partnerships, and provides certification incentives, robust data encryption, and localized cybersecurity protocols. The paper contributes to the body of knowledge on digital innovation in contract administration and offers practical recommendations for policymakers, practitioners, and researchers seeking to foster digital transformation in emerging construction markets.

Keywords: *Barriers; Contract Administration; Digital Twin Technology; DTT; Construction Industry; Sustainable Development.*

1. INTRODUCTION

Digital Twin Technology (DTT) is an emerging innovation for developing real-time virtual models of physical systems beyond the current state of the art (Grieves & Vickers, 2016). On the other hand, Contract Administration (CA) refers to the administrative functions related to dealing with contracts including issuing instructions, managing change procedures, dealing with completion and possession issues, resolving disputes, assessing entitlement for extension of time, advising all parties of their contractual rights

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and obligations, dealing with payment provisions, implementing contract, contract monitoring and quality assurance (QA), and contract interpretation (Davison & McCue, 2022). Nowadays, DTT is enabled in CA processes, such as compliance tracking and dispute resolution in sustainable projects. For example, DTT is used in Singaporean smart cities (Ai & Ziehl, 2024) and BIM based infrastructure monitoring in the United Kingdom (Li et al., 2019). CA in Sri Lanka remains predominantly manual, relying on paper-based documentation (Dunleavy et al., 2005), fragmented stakeholder communication via emails/ad-hoc meetings (World Bank, 2020), and reactive dispute management with 40% of projects delayed by contractual ambiguities (Hewage & Ruwanpura, 2021). BIM adoption is limited to <15% of design phases, hindering digital integration.

DTT have been repeatedly mentioned in the literature of asset management in the modern era as a conceptual enhancement (Grieves & Vickers, 2016). Using this developing body of knowledge, the current study offers empirical data on the operational integration of DTT into CA, thus re-engineering the two paradigms into a synchronised, data-driven compliance tracking and dispute resolution system. The practice of this real-time, data-driven transformation can be seen in two contexts: Singapore smart-city development and large-scale infrastructure projects in the United Kingdom (GovTech Singapore, 2022). Nevertheless, Sri Lanka's construction industry has been mostly limited to manual CA practices, fragmented stakeholder collaboration, and the lack of digital literacy (Dunleavy et al., 2005). Apart from the studies on DTT in design automation (Sobhkhiz et al., 2021) and CA with AI (Bolhassan et al., 2021), there are no previous studies regarding the DTT and CA integration in Sri Lanka. Naji et al (2024) highlighted that there are digitalization hindrances in Sri Lanka in addressing the construction issues. Thus, this study aims to identify the barriers to implementing DTT for CA processes in Sri Lanka and develop ways to overcome them.

2. LITERATURE REVIEW

2.1 WHAT IS DIGITAL TWIN TECHNOLOGY?

DTT involves creating a virtual implementation of a physical system, process, or asset that synchronises in real-time with data from sensors, Internet of Things (IoT) devices, and analytic platforms (Saad et al., 2025). By mirroring the physical entity's behaviour and lifecycle, it enables predictive modelling, simulation, and decision-making based on the entity's characteristics (Tao et al., 2018). DTT is an emerging field in the construction industry, aiming to provide solutions and improvements in various aspects of construction projects (Akanmu et al, 2019). Furthermore, DTT supports the construction industry's advancement toward the 5th industrial revolution and presents new opportunities to enhance the performance of construction projects throughout their entire life cycle (Moshood et al., 2024).

2.2 IMPLEMENTATION OF DIGITAL TWIN TECHNOLOGY FOR CONSTRUCTION CONTRACT ADMINISTRATION

DTT is useful for enhancing the contract administration in construction with transparency for monitoring, analysis, and communication, as well as enabling real-time worker and stakeholder interaction (Ammar et al., 2022). Further, Tao et al. (2018) highlighted that DTT helps to reduce risks, enhances compliance tracking, and improves the CA through real-time data sharing and automation of Workflows. For example, in Singapore smart infrastructure project, DTT has been used to pave the ground via automated progress monitoring and claims resolution with an immutable audit trail in the aspect of designing and CA (Shishehgarkhaneh et al., 2022). DTT digitises documentation and facilitates collaboration among stakeholders, updates in a single platform that reduces ambiguities in contractual terms, and helps to hold people accountable (Tao et al., 2018).

2.3 BENEFITS OF IMPLEMENTING DTT FOR CA

Table 1 provides ten (10) key benefits of implementing DTT in construction CA with supported verifiable academic references from global case studies from the UAE, Germany, and Hong Kong. By linking each benefit (i.e., greater transparency, cost savings, and sustainability alignment) to empirical evidence, which demonstrates DTT's prevention of disputes, improving compliance, and maximising the use of available resources. These findings collectively highlight the possibility of DTT capabilities to assist CA practice by combining real-time data analytics with contractual governance to achieve efficiency and accountability in CA within projects.

Table 1: Benefits of DTT adoption

Ref	Benefit	Description	Sources
A1	Transparency	With DTT, stakeholders can have a real time access to project data and that decreases information asymmetry and increase trust. With virtual models, clients and contractors have an opportunity to collaborate in monitoring progress, compliance and resource allocation.	(Lu et al., 2020)
A2	Enhanced efficiency	Automated workflows eliminate time-wasting documentation, approval and change order cycles. AI based analytics reduces the reporting time by up to 30–40 percent in the Australian infrastructure projects.	(Alnaser et al., 2024)
A3	Mitigation of risks	Predictive analytics predict with high certainty when contractual obligations are not met (such as delay, overrun) prior and in advance of corrective action, when possible. In U.S. transportation projects, it reduced the disputes by 25%.	(Management Association, Information Resources, 2022)
A4	Alignment with sustainable development	SDG 9 and 11 are the goals supported by DTT as we optimize material use and reduce waste. In the case of UAE, real time resource tracking reduced the site waste by 18%.	(Tao et al., 2018)
A5	Enhanced collaboration	Real time collaboration is possible on cloud based DTT platforms. In Singapore, shared virtual models led to 15% reduction in rework once rework was counted, for the contractual deliverables.	(Bado et al., 2022)
A6	Cost reductions	It contributes to savings in the long term because rework and delays are reduced. German study also showed that DTT cut project overruns by 20%, by following a budget correctively.	(Serugga, 2025)

Ref	Benefit	Description	Sources
A7	Monitoring compliances	DTT automates compliance checks of contractual terms. For example, DTT was used in UK projects to enforce the sustainability certification with 100% compliance with the standard.	(Boje et al., 2020)
A8	Improved decision-making techniques	Stakeholders can evaluate scenarios (design changes), test before implementation and improve the accuracy of decisions by 35% in Japanese megaprojects.	(Pal et al., 2023)
A9	Building maintenance	Maintenance needs predictions through a lifecycle of a project can be made by DTT.	(Kaewpoonsuk, 2024)
A10	Dispute resolution activities	Immutable audit trails reduce the number of ambiguities in contractual claims.	(Gupta & Jha, 2023)

2.4 BARRIERS TO IMPLEMENTING DTT IN CA

The barriers to DTT adoption in Contract Administration (CA) identified from the literature sources are presented in Table 2. Fifteen (15) barriers were identified and categorised using thematic analysis technique. Accordingly, five groups emerged, namely technological, organisational, economic, regulatory and cultural barriers for implementing DTT in construction CA.

According to the table, key technological barriers are fragmented data integration (USA), cybersecurity risks (Australia), human and procedural limitations (India and Australia), and resistance to digitization (Sri Lanka and Australia). Further, systemic and policy related barriers are reflected in economic barriers such as high costs (South Africa) and unclear ROI (Canada), regulatory gaps (Europe), and legal ambiguities (Singapore). Therefore, the need for holistic strategies becomes stronger because cultural resistance to abandoning traditional practices is a barrier to DTT adoption that could be consistent with global best practices and local contexts. The survey of the reported global barriers to digitalisation, shown in Table 2, is exhaustive, but the existing literature shows heterogeneity in context.

Edmundson (2022) focuses on cybersecurity issues in the context of high technologies, and Çetin et al. (2021) on the problem of interoperability in regulatory fragmentation, particularly in Europe. However, existing literature does not pay much attention to interdependencies: economic limitations B10-B12, say, often compound human-capital shortages B7 in developing economies. An obvious gap is the sociotechnical analysis that would help understand the way such barriers are formed; the digital-maturity models (Kaewpoonsuk, 2022) could be used to understand why such barriers as cultural resistance B15 in Sri Lanka are rooted in systemic digital immaturity, not individual attitudes. Theoretical anchoring is required to translate lists of descriptive barriers into diagnostic tools to enable specific interventions.

Table 2: Barriers to implementing DTT

Code	Category	Barrier	Description	Global example	Source
B1	Technological	Complexity in data integration	Data formats across tools, with different data formats across BIM vs. legacy systems (fragmented formats).	Infrastructure projects in USA	(Lucchi, 2023)
B2	Technological	Cybersecurity issues	Risks related to data breaches in IoT devices and cloud platforms.	Smart cities in Australia	(Edmundson, 2022)
B3	Technological	Limitations in interoperability	Incompatibility between DTT tool and other CA tools.	Construction sector in Europe	(Çetin et al., 2021)
B4	Technological	Issues in accuracy and data quality	Getting error sensor data on virtual models.	Automotive projects in Germany	(He & Mao, 2023)
B5	Technological	Limitations in available infrastructure	No infrastructure at all for the existing IoT/sensor systems in developing regions.	Housing projects in South Africa	(World Bank, 2020)
B6	Organizational	Refusal to accept digitalization	Contractors prefer manual CA processes.	Mega projects in Sri Lanka	(World Bank, 2020)
B7	Organizational	Existing skill gaps to DTT adoption	Missing professionals with the knowledge to integrate DTT and CA.	Construction firms in India	(Çetin et al., 2021)
B8	Organizational	Issues in stakeholder collaboration	Silos between contractors, clients, regulators, and work functions.	Infrastructure projects in Brazil	(Hewage & Ruwanpura, 2021)
B9	Organizational	Lack of team spirit and leadership support	Absence of commitment in other senior management to programs to fund DTT initiatives.	Renewable energy projects in UK	(McKinsey & Company, 2023)
B10	Economic	Higher implementation costs	Sensors, software license, training	Renewable energy projects in South Africa	(Lucchi, 2023)
B11	Economic	Minimum ROI (Return on Investment)	Uncertainty about long-term financial benefits of DTT adoption.	Smart cities in Canada	(McKinsey & Company, 2023)

Code	Category	Barrier	Description	Global example	Source
B12		Maintenance costs	Updating and maintaining DTT systems expenses	Transportation projects in USA	(Lucchi, 2023)
B13	Regulatory	Insufficient standardized frameworks	Absence of global protocols for DTT-CA integration.	Construction sector in Europe	(McKinsey & Company, 2023)
B14		Legislative uncertainties	Ambiguities in liability for DTT-generated decisions.	Smart contracts in Singapore	(World Bank, 2020)
B15	Cultural	Preference for traditional practices	Lack of willingness to stop using CA processes based on paper.	Construction contracts in Sri Lanka	(Hewage & Ruwanpura, 2021)

3. RESEARCH METHODOLOGY

Research methodology refers to the principles and procedures of logical thought processes that are applied to a scientific investigation (Fellows and Liu, 1997). Research methods, on the other hand, are merely tools. This research requires an in-depth exploration of implementing DTT technologies to improve CA. This can be achieved through examining the lived experiences of stakeholders. Qualitative methods are particularly appropriate for the capture of stakeholder views, contextual and unexpected themes (Creswell and Poth, 2018). Thus, a qualitative research approach was conducted to explore the subjective multiple barriers to DTT adoption.

Ten purposively sampled experts were interviewed using a semi-structured method, with thematic saturation reached when no new insights emerged. This methodology agrees with the rules of qualitative methodology, which do not give priority to breadth, but rather to depth, especially in the case of an expert panel that is homogeneous and explores a specialized subject (DTT-CA implementation). The collected data were analysed using thematic analysis. The analysis adopted a top-down approach, whereby pre-established themes derived from the literature synthesis initially guided the data interpretation process. Table 3 provides the profile of respondents, including their designation, years of experience, and the selection criteria for selecting them as experts for the study. The principles of ethical compliance were followed in the study. Ethics approval was sought and granted by the institution, and all the participants gave written informed consent. The data processing involved anonymization of participants and participation was voluntary. Information was stored safely to avoid unauthorized access, as it is the case with standard qualitative research procedures that involve human subjects.

Table 3: Participants' profile

Expert Code	Designation	Years of Experience	A	B	C	D
E1	Senior Quantity Surveyor	10	√	√	√	√
E2	Contract Administrator	12	√	√	√	√
E3	Commercial Manager	8	√	√	√	√
E4	Researcher	15	√	√	√	√
E5	Academic	14	√	√	√	√
E6	Construction Manager	18	√	√	√	√
E7	BIM Specialist	9	√	√	√	√
E8	Commercial Manager	11	√	√	√	√
E9	Civil Engineer	7	√	√	√	√
E10	Contract Specialist	13	√	√	√	√

A – Experience in Construction Contract Administration > 5 years

B - Awareness on DTT/ Experience on DTT

C – Minimum educational qualifications - at least a construction related degree

D - Possessing professional qualifications ‐ at least one among IQSSL, RICS, IESL, CIOB, LEED

4. FINDINGS

Even though, there were identified 15 barriers of adoption of DTT in Construction Contract Administration (CCA), the data analysis confirmed 13 critical barriers of adoption. The findings of the study uncover important pieces of information regarding the development of barriers to DTT adoption in the context of CCA in Sri Lanka. The barriers to implementing DTT for CA identified from the literature (15 barriers) were contextualized to the Sri Lankan context using in-depth interviews. Accordingly, a few barriers were modified, merged, or newly added. The research findings identified 13 barriers to implementing DTT in CA for the Sri Lankan construction industry, as outlined in Table 4. Further, the solutions were provided for the barriers through the thematic analysis of the in-depth interviews. These solutions provide actionable insights to the Sri Lankan construction industry.

From the thematic analysis of expert interviews, critical updates to the barrier framework were identified, such as the identification of new barriers and additional refinements to existing categories of barriers. According to Table 4, none of the barriers were removed from the literature findings while contextualizing to the Sri Lankan context. However, the modified barriers and newly added barriers are formatted as italicised and bolded. Thus, 6 barriers were modified by renaming, such as SLB2, SLB3, SLB4, SLB5, SLB6, and SLB7. In addition, the barriers B10, B11, and B12 have been merged as one barrier called financial constraints (SLB10). Further, the barriers B9 and B15 were merged and renamed as resistance from organisational culture (SLB9). One barrier was newly added for the SL context, specifically as vendor Lock-in (SLB13). Potential solutions for these barriers were proposed as shown in the last column of Table 4, based on the researcher's impetus and emerged from the expert discussions.

Among the 13 barriers to implementing DTT for CA in Sri Lanka, 3 barriers were overwhelmingly identified by the experts in the technological barrier category, such as cybersecurity risks, interoperability issues, and infrastructure gaps. Accordingly, the cybersecurity risks were considered most vulnerable because most firms panic about hackers accessing sensitive contract terms, as stated by E3. This was further explained by E1, recalling one of their past experiences, stating, "*the altered sensor data concealed an LKR 75 million (USD 250,000) concrete shortfall, resulting in a severe erosion of stakeholder trust in the digital system*". In further explaining, "*this incident underscores how DTT's data-dependent nature creates new attack vectors that malicious actors can exploit to manipulate contractual evidence*". This demonstrated the real-world consequences of cybersecurity risks. Like cybersecurity risks, equally problematic are interoperability issues in merging disparate digital ecosystems. E6 and E7 highlight the immense difficulties in reconciling different regional standards, whether combining Hong Kong's HKT specifications with the EU's ISO 19650 protocols or aligning the UK's BSI standards with international frameworks. These compatibility issues create significant friction in cross-border projects and even domestic operations using imported technologies. E4 adds that Sri Lanka's lack of a national digital engineering framework exacerbates these problems, resulting in fragmented data systems that cannot communicate effectively. Thus, the study proposes robust data encryption and localized cybersecurity protocols as the potential solution to the above two barriers. The next emphasized technological barrier is the infrastructure gap. The limitations in the electricity infrastructure in Sri Lanka were presented by E4 as follows: "*60% of rural construction sites lack stable internet connectivity fundamentally constrains real-time*

DTT functionality". These infrastructure gaps create a vicious cycle, where limited connectivity discourages DTT investment, which in turn slows digital infrastructure development. Therefore, the study proposes initiating a public-private infrastructure partnership and generating a DTT model through offline, capable methods as a solution to overcome the barrier.

In addition to the technological barrier category, the other three most stated barriers to implement DTT in SL CA in other barrier categories are financial constraints, generational divide, and skill shortage. When considering the financial constraints, E6 and E7 highlighted "*DTT consumes 5-7 % of project budgets in emerging markets, thus it is not unique to Sri Lanka among the competing priorities. We cannot afford it without subsidies*". Therefore, the provision of a subsidy by the government and the initiation of the adoption of the DTT model for a pre-determined phase of the construction project's CA would be the potential solutions for the barrier. Next, the resistance to technological change was pointed out by experienced professionals. This resistance is compounded by the generational divide and is significant to Sri Lanka as like financial constraints. It can be supported by a statement given by E6, *"I've used paper for 30 years—I won't trust a machine"*. Adding on to that, E4 describes a pervasive attitude as *"why fix what isn't broken?"*. Provision of mentorship programs for the staff of the organisation and allowing a hybrid workflow could be potential solutions to overcome the generational divide. Then, the acute skill shortage was noted as the most indicated barrier to implementing DTT in SL CA. The critical human resource limitation to implement DTT in Sri Lanka was mentioned by E5 as "*only two hundred (200) BIM-certified professionals are available nationwide in Sri Lanka*". Reinforce that statement, E7 indicated "*just 12% of local engineers have that BIM certification*". The skill gap extends beyond basic BIM competency to more advanced DTT applications, where E3 noted "*only 12% of Asian contractors have DTT-trained staff*". Thus, workforce development must accompany technological investment for successful adoption. Provision of incentives as a certification for DTT users and enhancing the partnership with the higher educational institute to incorporate the practical knowledge on DTT for construction will overcome the skill shortage to implement DTT for CA in Sri Lanka.

In addition to the above-mentioned six key barriers, there are other barriers to implementing DTT for CA in SL. Accordingly, creating protocols for sensor calibration and development of a framework for quality assurance and quality control for sensors could be a potential solution for data quality issues, which are mainly caused by errors in sensors. Further, pilot projects are suggested as solutions for the resistance that emerges from the organisational culture. Another considerable issue is the data privacy and government related barriers, where reforming the legal framework and developing laws for standardized digital evidence could be a solution. Besides, vendor-lock-in was identified as a new barrier while contextualizing the literature findings to the Sri Lankan context. E8 explained it as "*once a company chooses a specific vendor or platform to build and operate their digital twin, it becomes very difficult, expensive, or time-consuming to switch to another vendor or system later on*".

The barrier experience from this on the implementation of DTT for CA is highlighted by E9 as "*organizations may hesitate to adopt a digital twin solution if they fear they'll get locked into a system that restricts flexibility, innovation, or cost control in the future*". Therefore, the solution to this barrier, which stems from dependence on expensive proprietary software, could be to first implement the DTT in open-source DTT tools and software. In addition, findings suggest utilizing the government-led platforms rather than those from a private vendor, which could significantly reduce the risk.

In the sociotechnical systems (STS) tradition, obstacles to the adoption of DTT are traditionally categorised into five broad categories: Technological, Organisational, Economic, Regulatory and Cultural. This schema is justified by the fact that effective implementation of DTT is based on the dynamic interplay of technological (tools, infrastructure) and social (people, structure, context) aspects (Clegg, 2000). Technological barriers (SLB1-SLB5) include shortcomings in hardware, software or connectivity as well as poor interoperability between DTT solutions. Organisational barriers (SLB6-SLB9) concentrate on the intra-firm features like capacity, cultural attitudes and governance arrangements. Economic barriers (SLB10) are based on the distribution of resources and profitability. Regulatory barriers (SLB11-SLB12) are based on external regulatory regimes that are unable to keep up with technological innovation or fail to leave legitimate policy gaps. Lastly, cultural barriers are part of organisational barriers, and they include deep-seated norms, practices and worldviews that hinder transformative change. Analytically, these classifications are helpful in that they allow the development of interventions that are specific to the subsystem that needs to be remediated; technical solutions can be designed to overcome technological barriers, and policy reform can be designed to overcome regulatory barriers. As a result, the framework provides both practitioners and scholars with a consistent, holistic view of DTT-CA adoption, softened by the realization that resistances are complex.

Technological barriers (SLB1-SLB5) were the most common, and the cybersecurity risks were the most significant constraint because of such incidents as maliciously altered sensor data that can create significant financial damage and reduce the trust of the population. Infrastructure deficiencies were also acute, with 60% of rural construction sites having no stable internet connection, thus fundamentally restricting the real-time capability of DTT.

The solutions to these technological problems are the creation of local cybersecurity standards and the creation of public-private partnerships that will modernize infrastructure. Organizational and cultural barriers (SLB6-SLB9) pointed to a significant generational gap, i.e., the reluctance of veteran professionals to digital workflows (e.g., I used paper all my life, I am not going to trust a machine), as well as to acute skills gaps, such as the fact that there are only 200 Building Information Modelling (BIM) certified professionals in the entire country. In this regard, suggestions include hybrid processes and industry incentives relating to university certification programs.

Economic and regulatory impediments (SLB10-SLB12) revolved around financial constraints, with DTT taking up 5-7 % of total project costs, encouraging firms to adopt a phased approach to adoption, with specific subsidies. The issue of data privacy highlighted the necessity of legal reforms that would help to standardize digital evidence. Vendor lock-in (SLB13) presented a new obstacle, as the use of proprietary software limited flexibility. The corresponding mitigation strategy suggests developing open-source platforms led by the government.

The current discussion contextualizes empirical results in the existing literature in a systematic way. It supports the diagnosis of Edmundson (2022) of cybersecurity vulnerabilities in high-tech environments with the measurement item SLB2 (Cybersecurity Risks). Simultaneously, it complements the work of Çetin et al. (2021)

regarding the interoperability by recognizing Vendor Lock-in (SLB13) as a poorly studied economic limitation in emerging economies. In addition, The Generational Divide (SLB6) situates the cultural barriers described by Hewage and Ruwanpura (2021) within the systemic digital immaturity of the Sri Lankan context, thus expanding the focus beyond the personal attitudes and questioning the direct transferability of global North models. The argumentation that follows hence establishes the need of sociotechnical ecosystem adaptations.

Moreover, the inclusion of potential solutions transforms Table 4 from purely diagnostic to prescriptive. The link between the barriers and proposed potential solutions is presented in the following Figure 1.

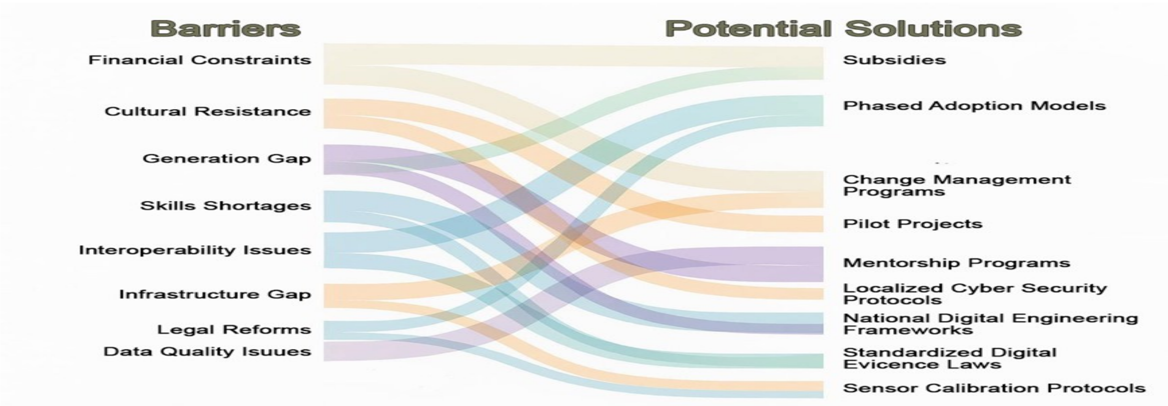

Figure 1: Barrier- Solution Pairing for DTT implementation for CA in Sri Lanka

In these findings, it is further shown that barriers are not static and evolve with changing technological/ contextual shifts. Sri Lanka's problems are unique socio-cultural and regulatory dynamics that compound the problem, global studies focus on skills gaps. Crossing the gap of awareness as a barrier to DTT adoption and introduction of vendor lock in or data quality issues indicate that the mission and purpose of DTT have been clearly understood better, and operators are increasingly advised to adopt a more tailored strategy that considers interaction between financial, technical and human components of DTT adoption.

Table 4 : Barriers to implementing DTT in CA in Sri Lanka

Literature review Findings			Expert Interview Findings		
Category	**Initial Code**	**Barrier in global context**	**Barrier in Sri Lankan context**	**Final code**	**Potential solutions**
Technological	B1	Complexity in data integration	Complexity in data integration	SLB1	Introducing Open BIM Standards - Adopt strategies and methodologies that enable data formats of different tools (e.g., BIM, IoT, legacy systems) to be unified using SDO or ISO 19650 compliant frameworks.
	B2	Cybersecurity issues	*Cybersecurity Risks*	SLB2	Robust data encryption and localized cybersecurity protocols.
	B3	Limitations in interoperability	*Interoperability Issues*	SLB3	Robust data encryption and localized cybersecurity protocols.
	B4	Issues in accuracy and data quality	*Data Quality Issues*	SLB4	Sensor calibration protocols and Quality Assurance and Quality Control (QA/QC) frameworks.
	B5	Limitations in available infrastructure	*Infrastructure Gaps*	SLB5	Offline-capable DTT model generation and public-private infrastructure partnerships.
Organisational	B6	Refusal to accept digitalization	*Generational Divide*	SLB6	Mentorship programs and hybrid workflows.
	B7	Existing skill gaps to DTT adoption	*Skills Shortages*	SLB7	University partnerships and provide certification incentives.
	B8	Issues in stakeholder collaboration	Issues in stakeholder collaboration	SLB8	Use tools such as BIM 360 or Procore to share real-time documents, track progress, and provide role-based access. IPD (Integrated project delivery) contracts Digital Twin Dashboards - Develop the dashboards based on roles (for instance, clients viewing milestones,

Category	Literature review Findings		Expert Interview Findings		
	Initial Code	**Barrier in global context**	**Barrier in Sri Lankan context**	**Final code**	**Potential solutions**
					or contractors viewing compliance) to improve transparency.
	B9	Lack of team spirit and leadership support	*Resistance from organisational culture*	SLB9	Variation management programs and pilot projects.
Economic	B10	Higher implementation costs	*Financial Constraints*	SLB10	Subsidies and phased adoption models.
	B11	Minimum ROI (Return on Investment)			Offer tax breaks or bidding advantages to firms that use certified DTT-CA frameworks.
	B12	Maintenance costs			
Regulatory	B13	Insufficient standardized frameworks	Insufficient standardized frameworks	SLB11	National Digital Engineering Mandates Co-Developing Protocol Scalability refinement by Test frameworks on government-funded projects
	B14	Legislative uncertainties	Data Privacy and government concerns	SLB12	Legal reforms and standardized digital evidence laws.
Cultural	B15	Preference for traditional practices	*Resistance from organisational culture*	SLB9	Training, Government Backed - Educate people in Revit and Navisworks to enable cross-platform data management
			Vendor Lock-in	SLB13	Open-source DTT tools and software, and government-led platforms.

Bold: Newly identified barriers from Expert interviews | *Italicised*: Slightly modifies barriers during expert interviews

5. DISCUSSION

This research explains the multivariate barriers to the adoption of Digital Twin Technology (DTT) in the Sri Lankan construction industry, examining technological, economic, organisational, cultural, and regulatory barriers. Major limitations are high financial costs- DTT licences are said to absorb about 20 % of the profit margin of small and medium enterprises (SMEs), skills shortage, and legal reforms. The results also point out the fact that importing global models is constrained by contextual factors including generational gaps and the newly discovered obstacle of vendor lock-in which shows a mature awareness of the complexity of adoption. Besides, these challenges are compounded by local issues, such as cultural legacies, established practices, and infrastructure gaps (especially in rural settings) as well as data-quality risks and systemic policy issues related to data privacy and digital evidence.

Methodologically, the research was a qualitative one using expert interviews (n 10, mainly large organisations/government) which may have under-represented SME and subcontractor views, which are vital in diffusion. Thematic analysis with a top-down approach might have limited emergent themes, and the lack of quantitative data does not allow ranking barriers and modelling interdependencies, which makes generalisation to other emerging economies and highlights the necessity of mixed-methods research in the future.

The empirical evidence indicates that there is a high level of interdependence between the identified barriers and therefore isolated interventions are ineffective. Economic constraints are compounded by technological constraints, e.g. estimated LKR 75 million losses due to data/connectivity problems preventing return on investment, and cybersecurity threats, and infrastructure shortages. The organisational obstacles such as lack of skills and cultural resistance also work in self-reinforcing loops. Since the confidence and feasibility of cybersecurity vulnerabilities and labour shortages have multiplier effects, sequential strategies that are coordinated are more suitable than standalone strategies.

The current study goes beyond the traditional cost-skill dichotomies by putting vendor lock-in into the forefront as a relevant, under-researched constraint in emerging economies. Sri Lankan empirical evidence shows that the use of off-the-shelf platforms by managers increases dependency on Western providers, which hinders local digital transformation (DT). Based on this, the paper critically examines standalone licensing models and finds viable, situational, culturally relevant solutions: hybrid workflows that can narrow the generational gap; phased adoption that can assist SMEs through subsidisation; and open-source platforms that the government can lead to minimise reliance on proprietary systems and promote standardisation. Adoption, in turn, is redefined as the organisation of local sociotechnical ecosystems instead of the complete imitation of Global North patterns. Finally, the paper supports a holistic approach that involves both hybrid workflows and adaptive legal architectures to align local realities with global innovation, which supports sustainable DT in the resource-limited environment in Sri Lanka.

6. CONCLUSIONS

The current research identified 13 context-specific barriers to DTT adoption in the CCA practices of the Sri Lankan construction industry. These barriers were financial, organisational culture resistance, and a severe BIM skilled labour shortage. Several solutions generated by the respondents were suggested to reduce these obstacles including phased adoption models with subsidies, hybrid workflows, and government-led, open-source platforms. Because Sri Lanka is a developing country, the sustainable construction industry of the country presents an opportunity-rich field of CA development through DTT. The current study responds to a topical scientific demand, as no previous empirical research has assessed this integration in the environment of Sri Lanka with its unique socioeconomic and regulatory environment. Future studies ought to aim at empirically supporting the recommendations made and systematically analyse the interdependencies of the related barriers. The research thus equips policymakers with contextual approaches in which they can negotiate adoption complexities. The concept of lack of knowledge in the main construct studies means that there is no previous empirical study on DTT-CA integration in Sri Lanka, and thus there is no direct comparability. In line with this, further studies are justified to empirically support the suggested solutions as well as to investigate interdependencies of the identified barriers.

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