APPLICABILITY OF DIGITAL TWIN TECHNOLOGY FOR QUALITY MANAGEMENT IN THE SRI LANKAN CONSTRUCTION INDUSTRY

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Abstract: The construction industry in Sri Lanka is grappling with challenges such as cost, time, and quality issues, which impact project delivery, productivity, and overall performance. The current Quality Management (QM) systems are primarily paper-based, labour-intensive, and inefficient, hindering the ability to identify and manage defects. To improve Quality Management performance, fully automated and intelligent systems are required. The application of Digital Twin (DT) can offer real-time insights to enhance Quality Management procedures. However, the Sri Lankan construction industry is lagging in adopting Digital Twin technology due to implementation barriers. This study aimed to explore the applicability of Digital Twin for quality management in the Sri Lankan construction industry. A critical literature review was conducted, involving 15 experts interviewed using semi-structured interviews. The study found that Digital Twin improves the efficiency and effectiveness of the Quality Management process by integrating with quality standards and regulations, improving communication, material quality control, automatic quality checks, transparency, improved quality documentation, stakeholder participation in quality decisions, and prompt resolution of problems. This study identifies barriers to implementing Digital Twin in construction and suggests overcoming them. The results of this study indicate that Digital Twin has a higher potential than the traditional method currently used for Quality Management in the Sri Lankan construction industry.

Keywords: *Construction Industry, Digital Twin, Quality Management, Sri Lanka, Technology*

1. Introduction

The construction industry holds an iconic global status, having a significant impact on both the social and economic development of any nation (Su et al., 2023). According to Bao et al. (2023), it contributes up to 5–10% of various nations' Gross Domestic Production (GDP). Despite its importance, the industry faces numerous challenges that hinder its productivity and efficiency (Perera et al., 2023), which has led to a global decrease in productivity over the last 40 years (Basar & Basar, 2023; Nguyen & Adhikari, 2023; Omrany et al., 2023). Moreover, Olanrewaju et al. (2017) reported that cost, time, and quality are the main root causes of productivity in the construction industry. Emphasising the significance of project quality, Khan et al. (2021) stated that project quality is often a neglected factor in the construction sector. Similarly, Wang et al. (2023) stated that Quality management (QM) is critical in construction, impacting project durability, financial returns, safety, and societal well-being.

Unfortunately, many construction companies prefer to stick to traditional QM methods like manual inspection and testing, traditional quality assurance/ quality control, checklists and paper-based documentation (Arisekola & Madson, 2023). Furthermore, Wang et al. (2015) demonstrated that traditional QM methods are ineffective due to their inability to detect flaws, reliance on paper-based records, difficulty in data analysis, inefficient communication, and difficulty managing large-scale projects. Moreover, these traditional methods also lead to errors, lower product quality, cost overruns, and restricting quality managers' ability to quickly identify and resolve errors (Tran et al., 2021). Therefore, the construction industry must adopt modern technologies to enhance QM and address its challenges (Tuhaise et al., 2023).

Although several digital technologies have been widely used in the construction industry to improve safety (Guo et al., 2021), costs (Vigneault et al., 2020) and schedules (Chen et al., 2021), technology specifically to improve QM in construction has received less attention (Luo et al., 2022). Digital Twin (DT) is one such solution that can help in QM during construction and assessment by providing real-time insight into the performance and behaviour of various parts and elements of the construction project (Attaran & Celik, 2023). Furthermore, while there are significant studies on the use of DT technology for QM in manufacturing and other industries, there is a dearth of research on the construction industry (Arisekola & Madson, 2023). Nevertheless, compared to other countries, Sri Lanka's construction industry faces challenges in adopting new technologies (Suriyarachchi et al., 2019). However, Perera et al. (2023) claimed that despite the barriers, the doors for digitalisation in the Sri Lankan construction industry are now open.

Therefore, considering the requirements of the industry and the research gap, it is critical to investigate the applicability of DT technology for QM in the Sri Lankan Construction Industry. As such, this study aimed to explore the applicability of

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Digital Twin for Quality Management in the Sri Lankan construction industry. The objectives formulated to achieve this aim are to explore the benefits of incorporating DT within the QM in construction, barriers to implementing DT and the strategies to address the barriers in the Sri Lankan construction industry. This paper initially presents the literature review on the application of DT for QM in the construction industry. The research methodology adopted is then explained followed by the key research findings in terms of the use of DT in QM, barriers related to the implementation of DT and strategies to overcome the identified barriers. Finally, conclusions are drawn subsequently.

2. Literature Review

The construction industry faces numerous challenges, and those challenges directly affect project delivery, productivity, and overall performance (Basar & Basar, 2023). For decades these challenges prevented the construction industry from being as effective as other industries (Nguyen & Adhikari, 2023). The main factors contributing to productivity in the construction industry are cost, time, and quality (Irfan et al., 2021; Khan et al., 2021). Meanwhile, quality is critical because defects or failures caused by quality problems affect project costs, structural failure, delays, rework, material and labour waste, legal costs, disputes, and customer dissatisfaction in addition to productivity (Sahil et al., 2020). However, quality often receives insufficient attention from the early stages of a project (Faraji et al., 2022; Khan et al., 2021). According to Sahil et al. (2020), the country's economy is experiencing drastic changes due to years of quality problems in the construction industry. Ultimately QM is a critical factor in the successful completion of a project (Fernando et al., 2016).

2.1 QUALITY MANAGEMENT IN THE CONSTRUCTION INDUSTRY

QM is an ongoing research topic in the 21st century. Although QM gained popularity in the 1980s and 1990s, future organisations operating in the Industry 4.0 era still struggle to implement the concept (Gunasekaran et al., 2019). QM is defined as a systematic planning, implementation, control, and improvement to achieve quality objectives (Dias et al., 2022) Moreover, Othman et al. (2017) identified four elements of QM which are Quality Planning (QP), Quality Control (QC), Quality Assurance (QA) and Quality Improvement (QI).

In the construction industry, quality is described as satisfying the requirements of the owner, designer, builder, and regulatory bodies (Sahil et al., 2020). Therefore, the quality of a project significantly affects its success and survival in a competitive environment (Khalek et al., 2016). According to the findings, it is evident that the proper QM can enhance productivity, ensure sustainability, meet client and regulatory requirements, reduce costs, and drive improvement (Othman et al., 2018). However, negligence or low-quality performance can result in construction accidents and injuries (Ogwueleka, 2013). In addition, QM in construction is interconnected with all project activities and is a shared responsibility among all project parties (Khalek et al., 2016; Khan et al., 2021). Due to these reasons to address the quality issues and enhance QM, advanced technologies are needed (Wang et al., 2015).

Significant improvements in digital technologies enable engineers and managers to improve quality in the construction industry (Luo et al. 2022). According to Liu et al. (2023), the incorporation of cutting-edge visualisation technologies such as Building Information Modeling (BIM), Augmented Reality (AR), Mixed Reality (MR) and DT hold the promise of revolutionising construction QM. The authors further stated that this integration has the potential to significantly improve construction quality and lead to more efficient practices in the construction industry. Among the various new technologies available for QM, DT stands out as the one choice, as it offers significant potential for improving QM (Omrany et al., 2023). The main advantage of this is the ability for real-time monitoring (Arisekola & Madson, 2023; Attaran & Celik, 2023; Omrany et al., 2023). This real-time data enables quality managers to quickly identify and resolve problems (Arisekola & Madson, 2023; Omrany et al., 2023). DT can improve the quality of the final product and reduce costs (Boje et al., 2020; Jiang et al., 2021; Omrany et al., 2023). Moreover, Attaran and Celik (2023) highlighted that DT can identify and resolve any problems that arise while constructing, improving quality and lowering complexity. Due to all these factors, the DT becomes an excellent option for improving QM.

2.2 DIGITAL TWIN

A Digital Twin (DT) is a virtual representation of a physical object, enabling real-time bi-directional interaction and coordination between the physical and virtual worlds (Attaran & Celik, 2023; Jiang et al., 2021; Madubuike et al., 2022; Opoku et al., 2021; Singh et al., 2021; Su et al., 2023). DTs gather and transmit real-time data, facilitating effective decision-making, improving operational efficacy, and enhancing productivity across various industries (Madubuike et al., 2022). Furthermore, DT has been one of the fastest-developing technologies in many sectors in recent years (Jiang et al., 2021; Madubuike et al., 2022; Nguyen & Adhikari, 2023; Omrany et al., 2023; Su et al., 2022).

Accordingly, DT can be categorised based on factors such as the level of integration, its applications, hierarchy, and maturity level. According to Grieves & Vickers (2016), DT has been categorised as Digital Twin Prototype (DTP), Digital Twin Instance (DTI) and Digital Twin Aggregate/Environment (DTA/E) based on the maturity levels. Digital Twin Prototype (DTP) refers to the prototype of an object that includes all the data needed to represent the virtual model that was created before producing its physical twin (Grieves & Vickers, 2017; Singh et al., 2021). The bi-directional information flow throughout the life cycle, which is a key characteristic of DT, was neglected in DTP (Sepasgozar, 2021). Digital Twin Instance (DTI) is linked to its physical counterpart (Singh et al., 2021), where data from real space is transferred to virtual space once a physical system is constructed to monitor and forecast system behaviour (Madni et al., 2019). Since the relationship between both systems is bi-directional, any change in one is replicated in the other (Sepasgozar, 2021). Digital Twin Aggregate/Environment (DTA/E) describes the use of the DT in multi-domain applications to fulfil a different need (Liu et al., 2021; Sepasgozar, 2021).

Based on the data integration level between the physical product and its virtual representation Attaran and Celik (2023) categorised DT into three subcategories such as Digital Model, Digital Shadow and Digital Twin. Digital Model involves manual data exchange between physical and digital objects, preventing direct reflection of changes in the physical object's state in the digital one and vice versa (Opoku et al., 2021; Singh et al., 2021). Digital Shadow involves a self-driven one-directional movement data flow between physical and digital objects, with data from the physical object flowing automatically to the digital but still manual (Liu et al., 2021; Opoku et al., 2021; Singh et al., 2021). Digital Twin involves a fully integrated two-way communication between a physical object and its virtual counterpart, allowing for automatic bidirectional data flow between the two, ensuring that changes in one object directly affect the other (Liu et al., 2021; Opoku et al., 2021). In this paper, the term DT refers to both Digital Shadow and Digital Twin.

2.3 APPLICATIONS OF DIGITAL TWIN IN THE CONSTRUCTION INDUSTRY

DT was first used in the manufacturing and aerospace industries (Opoku et al., 2023), but now it has gained significant acceptance across various industries as diverse as retail, healthcare, construction, automotive, agriculture, telecommunication, education, mining, and utilities, (Attaran & Celik, 2023; Madubuike et al., 2022; Su et al., 2023). Although the use of DT in the construction sector is still relatively new, it has been expanding over the last several years (Boje et al., 2020; Jiang et al., 2021; Opoku et al., 2021; Tuhaise et al., 2023). Moreover, Tuhaise et al. (2023) highlighted that the DT concept can address the limitations of BIM. In addition, the authors further mention that this could provide real-time data updates to the BIM model, enabling better decision-making for asset management and operation.

The construction industry has a great deal of opportunity to improve QM procedures through the application of DT (Boje et al., 2020; Jiang et al., 2021; Nguyen & Adhikari, 2023; Omrany et al., 2023). In their work, Madubuike et al. (2022) discussed that DT is useful at every stage of the construction industry life cycle, from the initial to the final. When DT is in the design and engineering phase, it helps bring the information model and the product physical model together, ensuring iterative optimisation of both models (Opoku et al., 2021). Further, throughout the construction phase, the use of DT makes it possible to monitor the process, identify potential issues, and modify plans of action to ensure that projects are completed safely, on schedule, under budget, and with standards of quality maintained (Attaran & Celik, 2023; Madubuike et al., 2022; Nguyen & Adhikari, 2023; Singh et al., 2021; Su et al., 2022). These solutions also make it easier to track resources, such as labour, materials, and equipment; they also help with safety monitoring, resource planning, and operations (Attaran & Celik, 2023).

In their studies, Attaran and Celik (2023) stated that by offering real-time insights into the performance and behaviour of the various systems and components of the construction project, DT solutions can aid in quality control and assessment in the construction industry. With the use of this technology, possible problems can be identified and fixed virtually before they are implemented physically (Tran et al., 2021). Moreover, using DT to identify and resolve quality issues reduces errors, rework, and costly delays, thereby producing higher-quality construction projects (Tran et al., 2021). For example, DT can be used to find cracks in columns or other constructions or to assess the quality of concrete (Attaran & Celik, 2023). Furthermore, Su et al. (2023) emphasised that DT has been implemented to improve the design efficiency of environmentally friendly buildings as the initial step for the entire construction project because design quality has a substantial impact on construction-related activities. In addition, Omrany et al. (2023) reported, that quality checks and continuous monitoring of performance and maintenance requirements can be performed because DTs provide accurate virtual representations of components. Meanwhile, Su et al. (2022) pointed out that it is important to check the quality of construction in real time to prevent major construction accidents. Furthermore, Omrany et al. (2023) highlighted that the construction sector may make significant gains in construction quality, reliability, and efficiency by utilising DT technology for QM.

For example, in a study conducted by Tran et al. (2021), they proposed a DT-based framework for automated quality assessment of prefabricated as-built building façades. That framework not only offers insight into the quality of the as-built prefabricated façades, but it also offers a visual quality assessment solution that makes it possible to locate construction errors and identify missing and additional elements in the digital models by comparing a 3D as-built model with a semantic DT (Tran et al., 2021). Another, Research by Wang et al. (2023), introduced a DT-enhanced method to solve the problems of existing prediction methods, predicting the quality of composite materials. This work highlights the potential of DT in quality prediction for composite materials.

However, DT has enormous potential in the construction sector, there are several barriers to overcome. According to the literature review findings, lack of clear definition (Opoku et al., 2023), time and cost (Attaran & Celik, 2023), Innovation in technology (Singh et al., 2021), the complexity of the construction industry (Madubuike et al., 2022), lack of standards and regulations (Omrany et al., 2023), privacy and security (Omrany et al., 2023) were identified as major barriers to implementing DT applications in the construction industry.

3. Methodology

DT technology has been successfully implemented in only a few developed countries, and the application of DT for QM in the Sri Lankan construction industry is limited. This research aims to investigate the applicability of DT for QM in the construction industry in Sri Lanka. Accordingly, this research intended to collect in-depth knowledge from the experts on the implementation of DT for QM in the Sri Lankan construction industry. Therefore, this research adopted a qualitative approach. A qualitative research approach is used when in-depth analysis is required on the data collected from people based on their experience (Ritchie et al., 2014).

The recruitment of experts was undertaken using a purposive sampling technique to ensure that the respondents have sufficient knowledge on DT and QM in construction. The purposive sampling technique involves experts in a specific field being selected for research purposes (Etikan, 2016) where the researcher's knowledge and judgment play a role in intentionally selecting the expert based on specific criteria (Obilor & Isaac, 2023). As such the quality criteria used to recruit the experts were considered as having an educational qualification in construction related degree, having at least two years of experience with any modern technology in the construction industry and having adequate awareness of QM in the Sri Lankan construction industry. Due to the limited availability of local experts who have knowledge and experience with DT in construction, the Sri Lankan experts who work abroad were also considered for this study. To identify suitable experts snowball sampling was also used, where the respondents helped to find other possible respondents (Biernacki & Waldorf, 1981). The concept of saturation was used to determine the sample size (Guest et al., 2006), where the sample size was decided at the point where no new knowledge was generated. Accordingly, 15 experts were selected as shown in Table 1.

Qualitative content analysis was carried out to analyse the primary data gathered through the semi-structured interviews. Content analysis facilitates the gathering of unstructured data to enable it to understand the characteristics and conclusions of recorded materials (Fellows & Liu, 2015).

Table 1: Profile of the Respondents

Interviewee code	Designation	Type of Organisation	Country where the experts work	Experience	Key Expertise Areas Related
E01	Executive Director, Country Manager	Consultancy firm	United Arab Emirates	5 years	BIM, Quantity surveying, Cost Management
E02	Associate Engineer - Quality Assurance	Manufacturing firm	Sri Lanka	2 years	Digital Twin, Automation Engineering, AI, Machine Learning
E03	Digital Twin Engineer, Researcher	Manufacturing firm	Sri Lanka	2 years	Digital Twin (Manufacturing)
E04	Senior Lecturer, Built Environment Discipline	Educational	Australia	14 years	Building & Construction, BIM, Construction Management, Smart Technology
E05	Research Programme Manager	Educational	United Kingdom	9 years	Digital Twin, Construction Automation, BIM
E06	Researcher	Educational	Hong Kong	2 years	Digital Twin, BIM, lean, and disaster risk reduction
E07	Lecturer	Educational	United States	6 years	Data Science, Data Analytics Informatics
E08	Lecturer	Educational	Australia	7 years	AI (Machine Learning/Deep Learning), Defects detection and facilities management
E09	Quantity Surveyor	Consultancy firm	United Arab Emirates	4 years	BIM, Quantity Surveying
E10	Site Engineer	Construction Firm	Qatar	5 years	BIM
E11	Quantity Surveyor	Construction Firm	United Arab Emirates	4 years	BIM, Cost estimation, Quantity Surveying

E12	Doctoral Researcher, Built Environment Discipline	Educational	Australia	14 years	AI (Deep Learning,), BIM, Project Management, Construction Management
E13	Senior Consultant Quantity Surveyor	Consultancy firm	Saudi Arabia	15 years	BIM, Value Engineering, Cost Management, Project Estimation, Cost Engineering
E14	Researcher	Educational	United Kingdom	2 years	Digital Twin, BIM, Construction Management
E15	Researcher	Educational	Australia	4 years	Digital twin, Smart City

Due to the limited number of practitioners who use DT in the construction industry, the interviewees were also selected from educational institutions, where the respondents demonstrated sufficient knowledge about DT technology in construction and QM.

4. Research Findings

The three objectives of the study to investigate the applicability of DT for QM in construction are to explore the benefits of incorporating DT within the QM in construction, barriers to implementing DT and the strategies to address the barriers in the Sri Lankan construction industry. Accordingly, this section elaborates the key research findings and discussions.

4.1 BENEFITS OF INCORPORATING DIGITAL TWIN TECHNOLOGY FOR QUALITY MANAGEMENT IN THE CONSTRUCTION INDUSTRY

According to the literature review, the quality issues in the construction industry have already been discussed. Furthermore, as per the opinion of the expert interviews' traditional QM practices used in construction are identified as Traditional QA /QC, Checklist, Site inspection, Site Test and Design Control. As E14 pointed out, this includes visiting the construction site and trying to determine whether or not several criteria are met. E09 further stated that they manually send the report as a PDF file to their supervisors if they do not meet such criteria. After that, according to their conclusion, further work is decided. Therefore, E01, E04, E05, E09, and E10 agreed that these are manual, time-consuming, and labour-intensive approaches. In the meantime, E13 has pointed out that due to the lack of proper quality management, many more obstacles will have to be faced. E01, E04 and E11 were similar and commented that rework can sometimes cost between 10% and 15% of the total construction cost. Additionally, E14 claimed that this method causes many problems such as communication problems and coordination problems. As a result, all the experts came to the same conclusion that the traditional QM system does not adequately address the challenges faced by the construction industry.

Accordingly, all 15 experts agreed that there is a critical need to use new technology for QM and they indicated that DT could well bridge this gap. Further, E01 attested that DT can significantly improve QM by providing real-time data from construction sites. In addition, E08 depicted that DT offers numerous benefits in the process, including data collection, planning, control, and assurance. Supporting this statement E04 described that DT improves the efficiency and effectiveness of the QM process by providing information, improving communication, saving time and cost, improving transparency, and prompt resolution of problems. Further, E07 revealed that by building a DT model, users can conduct trial and error, identify design issues, and identify areas of improvement at an early stage. In the meantime, E08 asserted that DT provides more granular information to resolve problems like clash detection, which is a common issue in building information modeling. Besides, E14 underlined that this data can be compared with as-built models and BIM models, using various technologies such as pictures, 3D models, laser scanners, and VR technologies. Therefore, E01 manifested that the DT enhances the QM process by overlaying project data with as-planned BIM models, providing a comprehensive view of the project and facilitating more accurate decision-making. On the other hand, E11 demonstrated that by utilising DT in these situations, the client can engage in QM and experience the building before it is constructed by experiencing the building's performance on the DT model. Furthermore, All the experts agreed that the DT allows for remote meetings, eliminating the need for physical meetings and resulting in faster and more efficient communication. Additionally, E13 claimed that it reduces coordination and communication issues, saving time spent on these tasks. Therefore, E15 claimed that DT makes it a more convenient and efficient way to connect with others.

In summary, the majority of the interviewees recognised DT not only contributes to QM but also saves time and reduces project duration. Therefore, the overall quality of construction projects can be significantly improved by applying DT to construction.

4.2 BARRIERS TO IMPLEMENTING DIGITAL TWIN IN THE SRI LANKAN CONSTRUCTION INDUSTRY

This section elaborates on the findings of primary data to explore barriers to implementing DT in the global construction industry. Most experts (E01, E04, E05, E09, and E13) agreed that the barriers to implementing DT have resulted in a low level of adoption of DT applications in the construction industry. Table 2 presents the barriers identified by experts in the study.

Table 2 : Barriers to Implement Digital Twin in the Construction Industry

Barriers	From Lit.	E01	E02	E03	E04	E05	E06	E07	E08	E09	E10	E11	E12	E13	E14	E15
Lack of clear definition	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time and Cost	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Resistance to Change	X	✓		✓	✓		✓	✓	✓		✓			✓	✓	✓
The complexity of the construction industry	X	✓			✓	✓	✓		✓	✓	✓			✓	✓	
Lack of Standards and regulations	X	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Privacy and security	X	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
Lack of skilled and trained professionals		✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Lack of translation of research into industry adoption		✓			✓	✓	✓		✓		✓					✓
Lack of government incentives		✓		✓			✓			✓	✓	✓				
Finding suitable hardware and software						✓			✓		✓		✓		✓	
Lack of Management Support		✓	✓	✓	✓			✓		✓	✓		✓			✓
Lack of technical knowledge		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	✓
Stakeholders' attitudes						✓			✓					✓	✓	
Non-involvement of professional bodies in encouraging DT		✓					✓			✓		✓				✓

According to the findings, the lack of a clear definition is one of the most prevalent barriers. Moreover, because the initial setup requires front-loaded work, and multiple equipment, all the experts highlighted that DT implantation requires significantly higher initial costs and time. Meanwhile, E12 mentioned that many people are reluctant to change their practices or invest heavily in new technologies due to the perceived time and expense involved. Additionally, E10 said that contractors, clients, and consultants in the construction industry often resist change due to their comfort zones. In addition, E01, E04, E05, E08, and E14 have highlighted that privacy and security are important to protect stakeholders' intellectual property rights when sharing designs. In addition, E13 indicated that stakeholder attitudes such as doubts about benefits, fear of job displacement, and concerns about data privacy and security significantly influence implementation. Moreover, E02, E04, E07, E10, and E15 emphasised that a significant degree of technical expertise and an understanding of digital technology are necessary for DT implementation.

In summary, all the experts agreed that all the above-mentioned global barriers affect Sri Lanka when considering the barriers to implementing DT in Sri Lanka's construction sector. Besides this, E01 showed that the current political instability in Sri Lanka creates a big barrier to implementing digital technologies such as DT. At the same time, E10 mentioned that creating standards and regulations for DT is also a big problem for countries with a corrupt political environment. Furthermore, E07 stated that one issue facing Sri Lanka is the lack of education, the fear of learning about such advanced technology, and the reluctance of educators to include modern technologies in the educational system.

4.3 STRATEGIES TO IMPLEMENT DT TECHNOLOGY IN THE SRI LANKAN CONSTRUCTION INDUSTRY

This section presents the strategies to address the identified barriers discussed under Section 4.2. According to the findings, Table 3 summarises the strategies suggested by experts which will help to improve the implementation of DT for QM in the Sri Lankan construction industry.

Table 3 : Strategies to implement DT technology in the Sri Lankan Construction Industry

Strategies	E01	E02	E03	E04	E05	E06	E07	E08	E09	E10	E11	E12	E13	E14	E15
Support from governmental and other regulatory bodies	✓	✓		✓			✓		✓	✓	✓	✓		✓	✓
Provide Education in universities	✓		✓	✓	✓	✓	✓	✓		✓	✓		✓		✓
Provide financial incentives	✓	✓	✓	✓		✓	✓	✓	✓			✓	✓	✓	✓
Collaboration between the industry and academia	✓			✓	✓	✓	✓	✓				✓	✓	✓	✓
Provide facilities (Software, Hardware)		✓			✓	✓	✓	✓						✓	✓
Establishing necessary policies and regulations		✓		✓	✓				✓		✓	✓	✓		✓
Emphasis on the advantages of DT	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓	✓
Get support and sponsorship from developed countries					✓	✓		✓	✓		✓	✓			✓
Pilot Projects	✓								✓	✓	✓	✓	✓	✓	✓

Incorporation of credit criteria for DT implementation				✓					✓		✓	✓		✓	✓
Cost-Benefit Analysis	✓				✓				✓		✓		✓		✓
Change Management		✓		✓						✓	✓		✓		✓
Training programmes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Change the industry attitudes		✓		✓				✓	✓	✓			✓		✓
Government influence	✓	✓					✓		✓		✓	✓	✓	✓	✓
Conduct Awareness programmes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Improve research and development	✓			✓	✓	✓	✓	✓		✓	✓	✓	✓		✓
Explores strategies of DT previously applied to other industries.		✓	✓				✓	✓					✓		✓

Experts pointed out that conducting awareness programs for students and construction professionals is a key strategy. E07 recognised that universities can provide education on DT to undergraduate and postgraduate students. In the meantime, E14 emphasised that since academic research has grown beyond industry, there is a significant gap between both of them. E08 further stated that although there has been a lot of research done on the development and usage of DT, the industry is remaining behind in implementing them. Meanwhile, E05 suggested creative strategies like making films and providing detailed technical presentations to demonstrate DT's benefits. In support of this, E10 recommended a pilot project be created to demonstrate the benefits to stakeholders. E12 commented that a success story about DT should be shared among the parties.

Among the expert interviewees E09, E10, E11, and E12 highlighted that government and regulatory bodies play a crucial role in promoting the use of DT in the construction industry. In addition, E07 added that the government can develop uniformly agreed regulations, force industries to adopt these regulations, incorporate credit criteria, and provide credit for the companies to implement the DT. Accordingly, E02, E03, E07, E08, E13, and E15 emphasised that learning from strategies that have been effective in encouraging the use of DT in other sectors can help increase DT adoption in the construction sector. Moreover, regular evaluation of digital DT implementations and feedback-based iteration can improve DT practice.

4.4 CONTRIBUTION OF DT TO IMPROVE QM PARAMETERS IN THE CONSTRUCTION INDUSTRY

This section initially aims to distinguish the contribution of DT to the improvement of QM parameters in the construction industry rather than the current technology. The four elements of QM were used to guide the questions that were intended to clarify the role that DT can play in construction quality management. As a result, additional sub-parameters were found for every parameter listed in Table 4.

Table 4 : Contribution of Digital Twin to Improve Quality Management Parameters

Parameter	Sub-Parameter
Quality Planning	Identify quality requirements
	Integration with quality standards and regulations
Quality Assurance	Prevention of defects
	Material quality control
Quality Control	Automatic quality check
	Detection of defects
	Transparent quality reporting
	Improved quality documentation
Quality Improvement	Use and analyse the historical data
Collaborative Quality Monitoring	Collaborative quality assurance processes
	Stakeholder participation in quality decisions
Other	Quality of risk management

In Quality Planning, E05 mentioned that the identification of quality requirements is facilitated through DT by providing a platform to clearly define and document quality standards and specifications. Further E07, E08, E10 and E13 manifested that integration with quality standards and regulations ensures that the project adheres to industry standards and regulatory requirements, thus promoting compliance and quality assurance. Moreover, E12 insisted that by incorporating standards like building codes, safety regulations, and quality requirements into a virtual building model, DT allows for real-time monitoring against established standards. Therefore E01, E04, E08 and E12 stated that this enables early detection of deviations, prompt action to correct them, early resolution of problems and continuous improvement of processes.

Accordingly in Quality Assurance, E11 declared that DT aids in preventing defects by facilitating proactive measures such as simulations, virtual inspections, and real-time monitoring to identify and rectify potential issues before they occur. As mentioned earlier, because the quality standards are embedded in the virtual model, many errors due to conflicts or design errors can be avoided during the design phase itself. Another perimeter is material quality control is improved through DT by enabling tracking and monitoring of material specifications, sources, and usage throughout the project lifecycle. Moreover, E14 addressed that DT can be used to determine how different materials behave under various conditions, including temperature, pressure, and other elements that affect the quality of the material.

The majority of the interviewees recognised that automatic quality checks are enabled by DT through continuous monitoring and analysis of project data, allowing for early detection of deviations from quality standards. Additionally, E03, E09 and E11 stated that DT collects details related to physical assets from various sources to achieve better quality control. In the meantime, E04 demonstrated that sometimes, an engineer can use a training engineer, site supervisor, or less qualified person to take pictures and upload them to a digital platform. The expert further explained that engineers at the head office can check defects and assign them for quick resolution, improving quality with less paperwork and formal documentation.

On the other hand, E06 emphasised that DT facilitated improved quality documentation by maintaining detailed records of project activities, inspections, and quality assessments, ensuring transparency and accountability. E09 highlighted the risk of document errors, distortions, or misplacement in traditional project management, which can lead to misunderstandings, disputes, and costly re-work. However, E07 attested that DT significantly reduces this risk by maintaining a centralised platform, secure storage, and easy accessibility of project documents. Meanwhile, E01, E05, E08, and E12 emphasised that access control here allows administrators to define access permissions, restricting unauthorised people from modifying or approving documents without proper authorisation. Similarly, E05 affirmed that DT's real-time dashboards and analytics enable transparent quality reporting, enabling stakeholders to effectively track and evaluate project quality performance. Collaborative quality monitoring is the next most important factor agreed upon by all experts to help improve QM in the construction industry. Similarly, E05 commented that DT supports collaborative quality assurance processes by providing a centralised platform for stakeholders to access and contribute to quality-related information and decisions. E13 further elaborated that by providing visibility and accessibility to relevant project data and insights, DT facilitated stakeholder participation in leading to better decision-making and faster resolution of quality-related issues.

5. Conclusion

The study identified the need for improved QM in the construction industry and the potential of DT technology to address this need. The literature findings detected that DT is a virtual representation of physical objects enabling real-time data flow. It has been recognised that DT enhances QM efficiency by providing information, improving communication, saving time and cost, enhancing transparency, and facilitating prompt problem resolution. However, DT applications in construction are mostly experimental, with practical implementations seen in countries like the UK, USA, Australia, and China. The research explored several benefits of DT and barriers to its implementation. The key benefits include Real-time monitoring, Defect detection, structural health monitoring, enhanced collaboration and effective communication, and effective decision-making. The barriers include high costs, technological complexity, lack of skilled professionals, insufficient standards, and stakeholder attitudes. In developing countries like Sri Lanka, additional challenges such as political instability and educational issues further hinder DT adoption. The barriers identified in the Sri Lankan construction industry pose significant challenges to effectively implementing DT for QM. In addressing such barriers, this study proposed strategies to effectively implement DT in Sri Lanka to improve the QM. The main strategies were to provide education & training, conduct pilot projects, improve awareness programs, and provide governmental support. By implementing these strategies, the Sri Lankan construction industry shall benefit in effectively managing its quality through DT implementation. The research justifies the applicability of DT in terms of the QM parameters such as Quality Planning (QP), Quality Control (QC), Quality Assurance (QA) and Quality Improvement (QI). The future research suggests a detailed investigation on the proposed strategies to convert those into short- and long-term actions. This paper will be of use to any interested readers and researchers who would like to explore more about the application of DT for QM in Sri Lanka or any other countries that are similar in nature.

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