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ASSESSING THE BENEFITS OF DIGITAL TWINS TOWARDS THE FORMULATION OF WHOLE LIFE CYCLE VALUE PROPOSITIONS: A SYSTEMATIC REVIEW

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Abstract

Digital twins have been advocated for adoption in the construction industry to tackle many of its inherent challenges. There has been a lack of clarity, however, in demonstrating their realized value with some enterprises facing difficulties justifying their investment. This study employs a systematic review method to extract empirical evidence demonstrating the value of digital twins. Some realized Digital Twins' benefits and costs were demonstrated in the articles, but there were no investment appraisal studies that provide a full account of value propositions. Future studies adopting case studies method are recommended to assess the value propositions of digital twins.

Introduction and background

Context

In the era of the fourth industrial revolution (Industry 4.0), businesses have been adopting digital technologies to drive further efficiencies in their processes. The proliferation of digital technologies has been transforming traditional workflows while promoting further productivity gains. The Architecture, Engineering, Construction, and Operation (AECO) industry, however, remains to be one of the least digitized industries (Agarwal, Chandrasekaran and Sridhar, 2016) with a very slow uptake of new technologies (Davies and Harty, 2013).

The AECO industry faces several inefficiencies such as low levels of productivity and a fragmented supply chain (Opoku et al., 2021). As a project-based industry, the delivery process is transient where the output is unique (Gann and Salter, 2000; Morris, 2004), and this inhibits the industry from adopting the benefits of repeatability like that in the manufacturing industry (Fernández-Solís, 2008). Projects are usually initiated for the purpose of creating new value (Winch, 2010).

Capitalizing on different digital technologies, a Digital Twin (DT) has been argued to be a driver of value in the AECO industry. A DT is a real-time virtual replica of a physical asset (Grieves and Vickers, 2017) with its use extending throughout the whole life cycle of the physical asset (Madni, Madni and Lucero, 2019). It employs a set of different technologies with the aim of achieving bidirectional flow of data between the physical asset and digital counterpart (Alizadehsalehi and Yitmen, 2023). This automated flow of data along with the use of data analytics can create several benefits including reduced rework, better energy management, and lower construction costs (Opoku et al., 2021). Despite their attested value and advancements in other industries such as Aerospace, and Manufacturing (Xie et al., 2023), the AECO industry has been slowly adopting this trend (Opoku et al., 2022).

In the context of their potential value, DTs can tackle many of the AECO industry's underlying inefficiencies and issues. However, due to the lack of clarity in their value propositions (Opoku et al., 2023), they have not been widely adopted in practice. Furthermore, construction enterprises find difficulties justifying the additional DT investment. It was even asserted that the value of DTs is yet to be defined (Pregnolato et al. 2022), and Shahzad et al. (2022) suggested the need for demonstrating their benefits as new technologies are adopted after their cost-effectiveness is demonstrated in real-world projects.

Research aim, question and objectives

The aim of this study is to investigate the reasons behind the lack of DT adoption in the AECO industry given the suggested lack of value propositions of DTs. Consequently, this research is motivated by the lack of a comprehensive identification of the actual value of DTs during the life cycle of built assets. Towards tackling the above problem, the proposed research question is *what is the value realized through the use of DTs in AECO projects?*

To tackle this question, the objectives of this study are threefold: (1) Investigating the value of DTs by identifying the associated benefits and costs with their use; (2) assessing the availability of empirical evidence supporting the claim of those benefits and costs; and (3) the identification of the life cycle stages during which value can be materialized.

Research background

Firstly, a clear boundary should be drawn between the difference of value and benefits. The two terms have been used interchangeably in literature (Laursen and Svejvig, 2016) while benefits are only a component of the total value. In basic terms, the realized value equates to the benefits less the cost depleted (Morris, 2013; Project Management Institute, 2019). Thus, the true value of an asset or a system involves an interplay between the accrued benefits and incurred costs. Benefits are those advantages provided to stakeholders (Ward and Daniel, 2006) that should be perceived by some stakeholders as a positive outcome (Bradley, 2010). The benefits derived from Information System (IS) investments can be either tangible, semi-tangible or intangible (Becerik-Gerber and Rice, 2009). Tangible and semi-tangible benefits are quantifiable while intangible benefits are non-quantifiable. Costs can be classified as direct or indirect.

One of the main desired benefits of the DT concept application in construction projects is the creation of value to deliver better project outcomes. Value creation has been denoted to be one of the nine fundamental properties of a DT as per the general concepts described in the Gemini Principles (Bolton et al., 2018). Within different architectures proposed for DTs (Ferré-Bigorra, Casals and Gangolells, 2022; Lu et al., 2020), the service layer is where DTs can deliver value to different stakeholders. At this layer, the user can interact with the system, and different functions can be deployed such as energy management and space utilization (Lu et al., 2020). During the design phase, DTs have the potential to reduce the possibility of rework, and deliver sustainable outcomes (Opoku et al., 2021). Construction costs can be minimized as well while improving the quality of deliverables (Opoku et al., 2021). Better decision making and predictive maintenance were some potential benefits suggested during the operation and maintenance phase (Khajavi et al., 2019). The literature was not very clear on demonstrating the cost behind the utilization of DTs. Costs were generally represented as barriers to adoption where difficulties in initial investments were stated (Madni, Madni and Lucero, 2019; Opoku et al., 2021).

For those reasons, the next section of this study will focus on collecting and analyzing literature sources related to the value of DTs realized by different stakeholders in the AECO industry. The method used for systematic collection of literature will be outlined, followed by the frameworks used for benefits and costs identification.

Methods and tools

To address the outlined research question, this paper will utilize a systematic review to organize and analyze the literature production in the realm of DT value delivery. This collation of evidence will follow the guidelines of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Page et al., 2021).

Scopus and Web of Science (WoS), well regarded as robust academic databases, were used for article identification. The search was carried out using the title/abstract/keywords field with three blocks of keywords:

(1) Digital twins: (digital twin*);
(2) Value: ("cost-benefit" OR "benefit-cost" OR "cost-effectiveness" OR "return on investment" OR "financial*" OR "feasibility" OR "value for money" OR cost* OR benefit* OR value* OR "business case");
(3) AECO industry: (aec* OR "construction industry" OR "built environment").

Given the nascence of DT research, and to conduct a comprehensive review of the literature, no filters were added for the date range. The results were filtered for journal articles and the search returned 99 articles in Scopus, and 87 in WoS.

The identification step was followed by the screening stage to assess the relevance of obtained articles. Initially, the obtained records were imported into a reference management software to remove duplicate records. Only articles written in English were retained for further screening. An initial screening of the abstracts and titles of the retrieved articles was followed to ensure that the focus of the publications was on DTs within the Built Environment. At this step, 45 articles were retained for a comprehensive review based on the eligibility criteria defined in Table 1 following which 12 articles were deemed eligible for the systematic review as shown in Figure 1.

Table 1: Inclusion and exclusion criteria

	Inclusion criteria	Exclusion criteria
Methodology	Case study, Survey, Experiment	Literature-based only
Focus	Studies providing some empirical or theoretical evidence regarding the potential benefits or costs of DTs	No identification or evaluation of DTs' benefits or costs
Depth	A comprehensive application of a DT	Study focusing on a particular technology rather than a comprehensive DT implementation

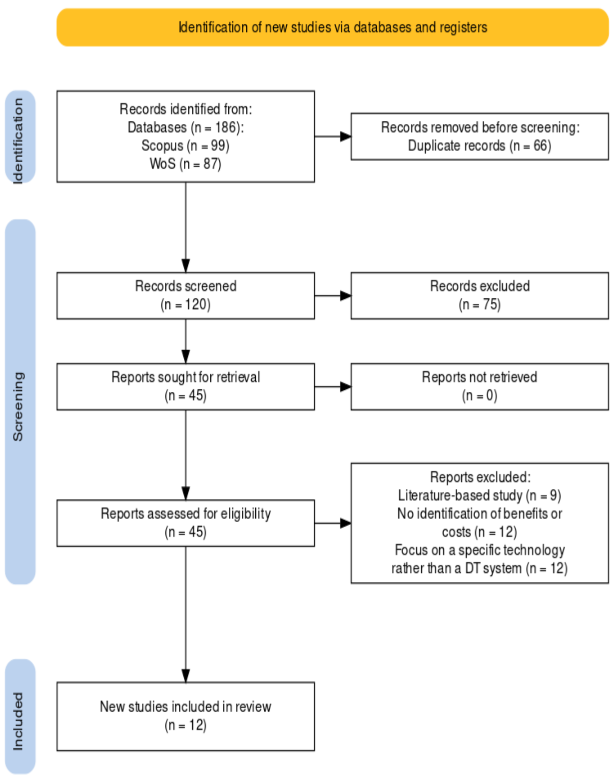

Figure 1: PRISMA screening process. Adapted from Haddaway et al. (2022).

Benefits and costs identification

The Centre for Digital Built Britain (CDBB) has adopted the Five Capitals Model developed by Porrit (2007) to profile the value of DTs (CDBB, 2021). This model has been developed to assess sustainable developments, and it is composed of five value categories namely: Natural, Social, Human, Manufactured and Financial capital. Natural capital includes the natural resources that are fused to provide goods and services. The Social capital includes the systems and institutions that help the Human capital work more productively when working collectively rather than in isolation. Manufactured capital is comprised of the assets that contribute to the production process and not the output. Financial capital is what allows the earlier categories to be traded and owned, and it encompasses their economic benefits and different costs.

To assess the value of DTs, their different benefits will be first identified from the collected literature and classified according to their tangibility. Tangible benefits can be easily quantified, while intangible benefits require a qualitative assessment that would subsequently impact one or more of the tangible benefits by means of a factor or percentage (Irani and Love, 2002). This classification of benefits was adopted by Irani and Love (2002) to develop a frame of reference for Information technology/ Information Systems (IT/IS) investment evaluation. It should be noted that this framework did not provide a taxonomy of IT/IS benefits, and hence it will be used as a reference to identify and cluster benefits. The focus of this process will be on benefits that are tangible and hence quantifiable.

For the costs, the identification process will follow the cost taxonomy developed by Irani, Ghoneim and Love (2006). The costs are classified as direct or indirect. Direct costs are associated with the use of technology components, while indirect costs capture that related to the organization and people dimension. This classification embodies both the technical and social components of a socio-technical system (Bostrom and Heinen, 1977) which could be deemed suitable for capturing a holistic DT utilization. Furthermore, this scope can capture all value categories highlighted in the Five Capitals Model (Porrit, 2007).

Investigation method of studies

Bakis, Kagioglou and Aouad (2006) outlined three main empirical investigation methods for evaluating the benefits of new technologies implementation as case studies, experiments, and surveys. Case studies were identified as the most robust of the three as they place the most emphasis on the context of the realized benefits. Experiments and surveys lack an emphasis on this context where the former imposes control factors for replication, while the latter does not depict how the benefits were created. Additionally, Hakimi et al. (2023) emphasized the need for conducting case studies to prove the business value of DT implementation.

The investigation method used in the selected articles will be highlighted. Articles using more than one investigation method will be highlighted as well. Finally, a further metric will be added to classify whether the study presented some quantifiable findings or not.

Results

Bibliometrics

To understand the broader research trends of DT publications, some quantitative bibliometric analysis was conducted on the 45 articles that were assessed for eligibility. Figure 2 illustrates an overall increasing trend in DT publications over the years.

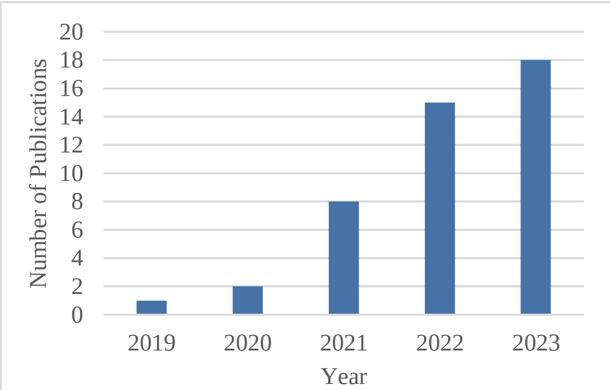

Figure 2: Bar chart showing the number of publications per year.

Based on a minimum number of two occurrences, a co-occurrence for author keywords was created as shown in Figure 3. In total, there were 24 occurrences where digital twins were the most common. There were no clusters for any of the *value* block keywords while the *AECO* industry's keywords appeared near the digital twin's cluster.

Content analysis

The classification of the selected twelve articles is illustrated in Table 2. Most of the studies followed a case study approach with only two of them employing more than one case study. Surveys were only used in three studies, and only one experiment was carried out. Four articles, adopting a case study approach, demonstrated some quantifiable benefits or costs from the use of a DT (Greif, Stein and Flath, 2020; Lin and Cheung, 2020; Love and Matthews, 2019; Zhang et al., 2023)

After reviewing the collected articles, a total of nineteen clusters of benefits were identified as illustrated in Table 3. Different benefits were matched to one cluster despite having different designations in different studies. For instance, increased transparency of information (Ammar et al., 2022), and transparency and data reliability (Esmaeili and Simeone, 2023) were matched to improved information management. The most common benefit was better environmental management followed by improved maintenance. Five other benefits were cited three times while the remaining were cited only once. Some of the presumed benefits were not matched to either of the

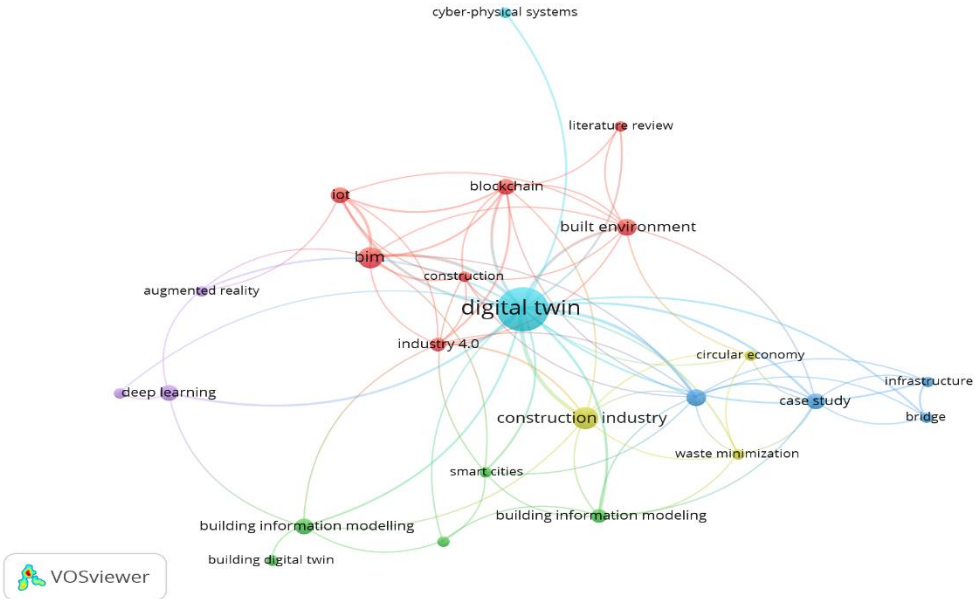

Figure 3: Author keyword co-occurrence map.

suggested benefits in Table 3 as they were essentially applications with different potential benefits but not benefits per se. For instance, Ammar et al. (2022) and Love and Matthews (2019) identified real-time reporting as a benefit while it could lead to other benefits that could be matched to more than one of the benefit clusters.

As for the benefits demonstrating some quantifiable findings, the study conducted by Greif, Stein and Flath (2020) presented a potential cost reduction of 25% in truck costs during silo movements between sites and plant. Another case study focusing on building heritage preservation demonstrated Indoor Air Quality (IAQ) improvements by an average of 9% and 1.2% for a restaurant and an exhibition room, respectively (Zhang et al., 2023). Love and Matthews (2019) illustrated different benefits across several case examples. In an Iron Ore Mine, the studied benefits were reported to result in a reduction cost of 94.25% in documentation cost. The time to produce a drawing was reduced to 2 hours from 40 hours with the use of a DT instead of a traditional Computer-aided Design (CAD) approach. Furthermore, the time required to address Request for Information (RFI) documents can be reduced by 91.67% person-hours in addition to improving the overall information management process of documents. The next case was a Magnetite Iron Ore Processing Plant, and the findings suggested an overall improvement in the information management process. This improvement has led to an improved site management since that design information was directly available for personnel on site. An improvement in installation efficiency as well as a reduction in cabling wastage were also reported, which suggests the delivery of an improved output.

In their next case of an Oil Refinery, improved information management, and improved site management were also reported. Monitoring the progress of person-hours worked on site has improved resource management. The DT was also reported to ensure asset integrity, which suggests an improved output. In their final study of a Rail project, there was a better handover of data from the construction phase to the operation and maintenance. DTs have also demonstrated their effectiveness in digital asset management.

Regarding the costs identified, only three publications outlined some relevant findings. Ammar et al. (2022) identified (1) Data understanding, preparation and usage, (2) Costs of implementation, and (3) Social costs, and it was the only source that identified indirect costs. Esmaeili and Simeone (2023) outlined data collection, platform and interoperability costs. Lin and Cheung (2020) highlighted the hardware cost, and it was the only reference that provided some minor quantification for the cost of wireless sensor networks used.

With respect to the life cycle stage of the studies, the operation and maintenance phase was the most common followed by the construction phase as illustrated in Figure 4. The benefits during the decommissioning phase were only demonstrated once.

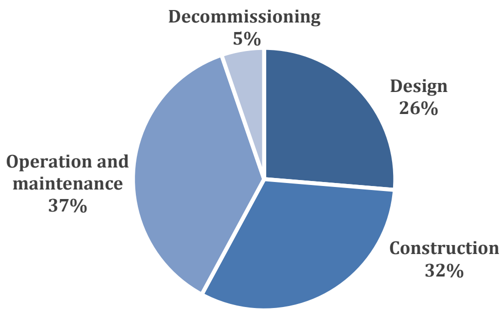

Figure 4: Distribution of Life cycle stages with demonstrated benefits from selected articles.

Table 2: Investigation method presented in the selected articles.

No. of Articles	Investigation method
6*	Case Study
2†	Case studies
1‡	Case study and survey
1§	Experiment
2**	Survey

*: (Greif, Stein and Flath, 2020; Lin and Cheung, 2020; Ogunseiju et al., 2021; Tagliabue et al., 2021; Tita et al. 2023; Zhang et al., 2023)
†: (Esmaeili and Simeone, 2023; Love and Matthews, 2019)
‡: (Ammar et al., 2022)
§: (Adibfar and Costin, 2022)
**: (Meng, Das and Meng, 2023; Shahzad et al., 2022)

Discussion and conclusions

This study has provided an overview on the realized value of DTs, based on empirical evidence, by identifying the associated benefits realized through their use. Different academic literature sources were retrieved from several databases to identify such. The findings demonstrated some benefits such as better environmental management and improved maintenance which were the most suggested benefits of this technology. Initial hardware costs, data infrastructure and handling were identified as the main cost elements. The findings suggest that the benefits of this concept can span across the whole life cycle of an asset. Most of the tested benefits were demonstrated during the operation and maintenance yet this finding does not suggest that this is the phase where stakeholders can realize most of the DTs' value. None of the studies presenting quantifiable findings investigated the benefits of DTs during the decommissioning phase.

From the selected articles, the first was published in 2019 which could suggest the impact of the Gemini principles (Bolton et al., 2018) in publicizing the value creation capabilities of DTs. The results, however, demonstrated a lack of research inquiries investigating the value realized with the use of DTs which is supported by the lack of author keywords related to value. There were also no studies providing a comprehensive record of the value realized by DTs. It was observed that all studies have either focused on benefits or costs, but not both. Other investigations focused on application areas only without providing an integral assessment of value.

Love and Matthews (2019) demonstrated some quantifiable findings in their study with respect to the benefits realized. The case examples used in this study included both vertical (building) and horizontal (infrastructure) projects which could suggest the varied applications of DTs in the AECO industry. The publication date of their paper, however, implied an early development stage for DTs in both the industry and academia, and hence their focus was on a System Information Model that can enable a DT. They also focused on providing an account of some benefits without extending appreciation to the costs involved.

Table 3: Benefits and their frequency in articles.

Benefit	References	No. of references
Better environmental management	Lin and Cheung (2020) Meng, Das and Meng (2023) Shahzad et al. (2022) Tagliabue et al. (2021) Zhang et al. (2023)	5
Improved maintenance	Ammar et al. (2022) Lin and Cheung (2020) Tagliabue et al. (2021) Tita et al. (2023)	4
Better scenario analysis	Adibfar and Costin (2022) Ammar et al. (2022) Zhang et al. (2023)	3
Improved information management	Ammar et al. (2022) Esmaeili and Simeone (2023) Love and Matthews (2019)	3
Improved output	Ammar et al. (2022) Love and Matthews (2019) Shahzad et al. (2022)	3
Improved site management	Esmaeili and Simeone (2023) Greif, Stein and Flath (2020) Shahzad et al. (2022)	3
Improved stakeholder collaboration	Ammar et al. (2022) Esmaeili and Simeone (2023) Love and Matthews (2019)	3
Better emergency and crisis management	Lin and Cheung (2020)	1
Better health and safety	Ogunseiju et al. (2021)	1
Better resource management	Esmaeili and Simeone (2023)	1
Better risk management	Shahzad et al. (2022)	1
Higher customer satisfaction	Shahzad et al. (2022)	1
Improved documentation	Love and Matthews (2019)	1
Improved efficiency	Love and Matthews (2019)	1
Improved procurement	Love and Matthews (2019)	1
Improved productivity	Love and Matthews (2019)	1
Improved progress monitoring	Esmaeili and Simeone (2023)	1
Improved supply chain management	Esmaeili and Simeone (2023)	1
Reduced execution time	Shahzad et al. (2022)	1

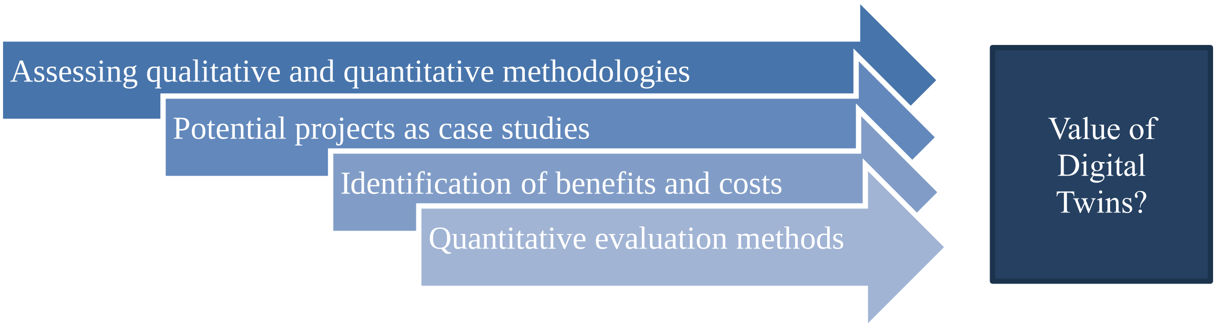

Figure 5: Research agenda.

In general, most of the studies did not present quantifiable findings which are the most sought after by practitioners when building a business case for additional investments. There was also some misclassification of benefits as an enabler of other benefits, with different designations used by different authors. The demonstration of quantifiable costs was even more limited than those of benefits. Empirical evidence coupled with quantifiable findings was only presented in four articles. This implies the need for a comprehensive assessment of the value delivered by DTs based on empirical evidence. A comprehensive cost-benefit analysis, or other quantitative evaluation methods, are recommended to tackle this issue, or to potentially identify the limitations of DTs. Further assessment of the different quantitative appraisal methods for DT investment should be conducted to recommend the most suitable one. It is also recommended to conduct research to develop a benefit and cost taxonomies for DTs to assess the viability of this innovative system. The suggested lack of DT adoption could be related to its high cost of implementation or upfront investment. This requires further appreciation to the barriers to entry experienced by enterprises at both an organizational and people level.

One limitation of this study was the adoption of IS/IT-investment evaluation frameworks due to the lack of available DT-cost or benefit taxonomies. The used framework was not prescriptive and the development of a framework with defined benefits and taxonomy can lead to a more robust identification of value constituents. Another limitation was the lack of mapping the relationship and interdependencies between different clusters of benefits. Future studies could develop a stock and flow diagram to capture any interdependencies which would ultimately lead to more refined benefit clusters.

Moving forward with this study, the research agenda will extend this theoretical framework by investigating the suitable methodologies for assessing the value of DTs in the AECO industry as illustrated in Figure 5. The findings of this study have already suggested that case studies are robust for assessing the value of new technologies, and this method would follow a qualitative inquiry. Other potential methods to assess this problem include quantitative evaluation techniques such as Cost-Benefit Analysis or Multi-Criteria Decision Analysis. In either case, the theoretical insights obtained from case studies will inform the design of the quantitative assessment. By drawing on both qualitative and quantitative evidence, this ongoing research could result in a comprehensive analysis of the value problem of DTs. The results obtained from this study will be used to validate the outcome of the primary research. By conducting this research, valuable insights could be recommended to various stakeholders in the AECO industry including practitioners and policymakers. Furthermore, the primary research could hold potential academic implications, enriching the existing knowledge base.

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