



# Digital Twins for Building Renovation – *What is the Added Value?*

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**Abstract.** Driven by Europe’s ageing building stock and the EU’s sustainability targets, renovation of existing buildings has become increasingly important. Building renovation typically comprises three types of activities (*operations & facility management, condition assessment & monitoring, and transformation planning*), each involving key decisions that can benefit from advanced decision support systems such as digital twins (DTs). DTs carry the promise of improved decision-making about, as well as the monitoring and understanding of, the twinned entity. This paper investigates how DTs can support, and add value to, the decision-making involved in building renovation and how the added value of these DTs can be assessed and (ideally be) quantified. In doing so, this paper focuses primarily on *operations & facility management*-related activities. By connecting use cases with quantification methods, this paper suggests pathways to evaluate and prioritise DT investments in the context of building renovation.

**Keywords:** Digital Twins · Building Renovation · Added Value of Digital Twins

## 1 Introduction

The renovation of existing buildings has gained importance due to an ageing building stock<sup>1</sup>, combined with the EU’s sustainability targets, including climate neutrality, improved energy efficiency, and reduced greenhouse gas emissions [18, 20]. Notably, 85% of buildings within the EU<sup>2</sup> were constructed before 2000, while 75% of these buildings have a poor energy performance [19]. Even more, at a global scale, over 90% of present day’s buildings will still be in use by 2050, prolonging the impact of inefficient buildings on overall energy use and emissions [28, 37, 42]. Consequently, effective renovation strategies are especially critical in Europe, where buildings contribute substantially to both energy consumption and carbon emissions. In response, governments and international

<sup>1</sup> In the construction domain, this refers to the ‘stock’ of buildings as presently in use.

<sup>2</sup> Including associated overseas countries and territories (OCT), such as Greenland.

bodies have introduced policies and targets to accelerate renovation. For example, the EU’s climate strategy and regulations call for a dramatic improvement of the energy performance of buildings [18, 20].

At the same time, undertaking renovation projects remains a complex challenge, since, unlike the construction of new buildings, renovation involves working with existing structures that often hide unforeseen issues, making project planning and execution difficult [26, 46]. Even more, uncertainty is an inherent trait in renovation, as project teams might not be fully aware of a building’s condition until actual work is underway. As a result, performance outcomes can be hard to predict [31, 49]. A further hurdle is the frequent lack of (digital) documentation for older buildings. Many legacy buildings have incomplete or out-of-date plans, forcing renovation teams to spend considerable effort on surveys, measurements, and planning for later maintenance [49, 70].

In this context, *digital twins* (DTs) promise to improve decision-making by providing a detailed *digital model* of a building, integrating real-time sensor or management data, visualising the current state, simulating renovation options, monitoring progress, and supporting operations with real-world data [25]. As such, DTs can provide ongoing added value through continuous monitoring, predictive maintenance, and performance optimisation [4, 48]. This paper frames DTs in terms of the value they add to renovation decisions rather than only technical capabilities.

Nevertheless, decision makers – building owners, and contractors question whether the added value justifies the investments [12, 49]. As argued in [59, 60], investments must be offset by the value DT functionality brings to decision-making. Trauer et al. [66] highlight the importance of identifying added value by linking DT functionalities to renovation phases and measurable outcomes, thereby connecting technical capabilities with practical decision-support needs. As DTs rely on *virtual model(s)* of the twinned entity [29], this return-on-investment question relates to ViA (Value in Action) and RoME (Return on Modelling Effort) [54].

In sum, the renovation sector must determine DT benefits and methods to measure them. Accordingly, this paper investigates reported use cases and how their added value can be assessed and quantified, focusing on *operations & facility management* – the longest and costliest stage of a building’s life cycle.

The remainder of this paper is structured as follows. Section 2 provides a brief exploration of the renovation industry, the typical ingredients of renovation processes, and the potential use of DTs. Section 3 discusses the approach used to collect relevant literature and analyse the selected sources. In Sect. 4, we discuss the identified DT use cases pertaining to *operations & facility management* activities. Finally, before concluding, Sect. 5 reflects on ways to qualify and/or quantify the added value of DTs across the identified use cases.

## 2 Background

Building renovation is not a stand-alone task but an integral and recurring part of a building life cycle. For instance in [24], the IG Lebenszyklus Bau [24], an

Austrian industry consortium comprising real estate developers, planners, facility managers, and public sector stakeholders, defines a building's life cycle as involving six main phases: *strategy*, *initiation*, *planning*, *execution*, *usage*, and *transformation*, where it is important to stress the intended cyclicality. Though alternative building life cycle frameworks exist, see e.g. [1,56], we primarily use the framework by IG Lebenszyklus Bau [24], as it enables us to (in future research) conduct case studies within the Austrian building sector.

Renovation activities primarily occur during the last two phases: usage (e.g., maintenance and adaptation) and transformation (e.g., repurposing, partial deconstruction, or redevelopment). For the purpose of this paper, the renovation process is viewed as encompassing three specific and interrelated activities embedded in the IG Lebenszyklus Bau [24]: *operations & facility management*, *condition assessment & monitoring*, and *transformation planning*. The *operations & facility management* activities are situated within the *usage* phase and involve the ongoing management and performance optimisation of a building. The *condition assessment & monitoring* activities are also part of the *usage* phase, and serve as a transitional activity to inform and prepare the groundwork for subsequent planning decisions. The *transformation planning* activities aligns directly with the *transformation* phase, and focuses on developing strategies based on assessed conditions, future requirements, and long-term goals.

Regulatory pressures, such as the European Green Deal [20], along with its Renovation Wave Strategy [18], push the renovation industry to modernise the ageing inventory. Renovation work, nevertheless, is prone to inherent complexity and uncertainty. Unlike new buildings, old buildings tend to have insufficient and poor documentation, while building data is commonly lost or degraded over decades of operation, and maintenance histories are limited [76]. That lack of reliable data implies that the actual condition of buildings and systems is often unclear until demolition or inspection, often resulting in unexpected problems.

Furthermore, retrofitting current buildings for sustainability faces critical technical challenges, based mainly on structural constraints and outdated systems. Older buildings often were not constructed to accommodate the extra load of integrated elements such as solar panels or green roofs. Necessary structural reinforcements for this are often very costly. Moreover, incorporating new technologies with obsolete electrical, plumbing, and heating, ventilation, and air conditioning systems is intricate, pricey, and needs careful planning to ensure that building operations are not affected [26].

The construction industry and, thus, as an essential part of it, the renovation sector is currently undergoing a transformative change through the adoption of advanced technologies, as the need arises for enhancing the efficiency, sustainability, as well as decision-making during the whole building life cycle [55,63]. According to Rajala et al. [55], the renovation business has grown significantly, particularly in developed regions, due to ageing building stock and stricter environmental regulations. In this context, technologies like Building Information Modelling (BIM) and DTs have emerged as critical drivers of this shift [63]. For instance, as stipulated by Nguyen and Adhikari [44], in the context of the

construction industry, DTs are based on the technology of BIM, providing structured environments, design documentation, and life cycle modelling. DT systems enhance the capabilities of BIM by allowing for real-time tracking, predictive maintenance, as well as operational optimisation through IoT, sensor networks, and machine learning [44]. DTs and BIM and their functionalities are reported to gain [10] more importance and popularity as a possible solution since the construction sector faces pressure to meet stricter environmental targets.

Early applications [33, 70] indicate that DTs can help decision-making in renovation processes by providing an accurate digital capture of a building’s current condition. Even when original documentation is missing, DTs support the creation of as-built models, allowing for better structural analysis and environmental monitoring. Through real-time data integration, DTs aid in early issue detection and strategy evaluation, improving decision-making [48]. During planning, DTs allow stakeholders to simulate various strategies and evaluate their implications before implementation [74]. In the construction execution phase and beyond, DTs support progress monitoring by enabling real-time tracking of components, performance metrics, and equipment interactions. These functionalities also extend to predictive maintenance and energy optimisation during and after construction, ultimately enhancing decision-making and improving outcomes in cost, time, and quality [4]. In addition, Nielsen et al. [45] state that early-phase planning is vital to sustainable renovation, as setting clear goals and criteria guides the direction of the entire process. Decision support tools that facilitate this step help stakeholders integrate sustainability considerations from the outset, fostering informed discussions and aligning objectives [45].

Nevertheless, challenges for the adoption of DTs for renovation persist. Reliable real-time data acquisition from existing buildings is often difficult, since retrofitting sensors can be invasive, complex, as well as costly. Integration with existing BIM models and legacy systems is further complicated by a lack of standardised data formats, fragmented documentation, and limited interoperability across the involved platforms [27, 31]. Effective use of advanced DT functionalities also depends on robust data governance, skilled personnel, sufficient digital literacy, and strong cross-disciplinary coordination. Despite these barriers, DTs are increasingly recognised as a key innovation for addressing systemic inefficiencies in renovation processes [48].

### 3 Research Design

The research reported on in this paper involved three stages. The first step was to collect relevant literature reporting on how DT functionalities are applied and valued within the renovation industry. Literature was selected by means of a systematic search of established academic databases, including *Scopus*, *Web of Science*, *IEEE Xplore*, and *Google Scholar*<sup>3</sup>. Queries were constructed using

<sup>3</sup> Where the latter was primarily used to ensure *recall*, as Scopus, Web of Science, and IEEE Xplore do not necessarily cover all reviewed outlets, especially considering the multi-disciplinary nature of the subject.

Boolean operators to combine key concepts and ensure comprehensive coverage. For example, queries included combinations such as “Digital Twin” AND “building renovation”, “Digital Twin” AND (renovation OR retrofit OR refurbishment), and “Digital Twin” AND (“value quantification” OR “RoI” OR “LCCA”). These base terms were further expanded with logical OR operators to include synonyms and related keywords relevant to the topic. For instance, a query in Scopus was formulated as: “Digital Twin” AND (“renovation” OR “retrofit”) to capture literature on DTs in renovation contexts. Additional queries targeted specific aspects by combining DT terminology with domain-specific keywords. Related concepts were also considered when constructing these queries. This Boolean search strategy ensured that differing terminology across disciplines was accounted for and that relevant publications were not overlooked due to vocabulary differences. Additionally, backward and forward citation tracking was applied, the reference lists of key papers were examined (backward tracing), and newer works citing those key papers were identified (forward tracing), to uncover further relevant studies beyond the initial keyword searches.

To be included in the review, sources had to meet three key selection criteria. Papers had to (1) have *relevance of functionality* in the sense that it should describe at least one functionality commonly associated with DTs, (2) be situated in the *context of renovation* in terms of the actual renovation or the operation of existing buildings considered for renovation, and (3) have *clarity of application* in the sense that the source should provide a clearly described application, methodology, or evaluation of the technology. The review emphasised peer-reviewed academic papers as the primary body of literature, which was supplemented by selected industry reports from reputable organisations for additional practical insights. Furthermore, only publications in English and generally those published within the last 10–12 years were considered, ensuring the research reflects contemporary developments. However, a few exceptions were made for foundational or frequently cited earlier works whose early contributions remain highly influential in the field.

To ensure a comprehensive and inclusive analysis, the scope of the literature study was not limited to publications that adhere to a narrow definition of a DT. Instead, it includes literature describing systems or processes which deliver functionalities commonly associated with DTs, such as real-time monitoring, simulation and scenario analysis, or predictive maintenance enabled by predictive analytics. This functionality oriented lens enabled a more accurate representation of how DT-like technologies are being implemented and discussed in the context of building renovation, even if different terminology is used.

In the second step, the selected papers were used to create a framework to map how DT-related functionalities are applied in, and adding value to, decision-making across the renovation process. This involved an examination of different use cases of DT-related technologies across key stages of the renovation process, like planning, condition assessment and monitoring, as well as operations and facility management. In doing so, a functionality oriented approach was taken,

rather than a strictly terminological one, due to the inconsistent usage of the term “Digital Twin” in the built environment domain.

To structure the analysis, a framework of DT functionalities was iteratively developed based on patterns identified in the literature. These functionalities represent recurring technological capabilities that are typically associated with DTs in the context of buildings and infrastructure. As the review progressed, the framework was refined or adjusted to reflect the variety and specifics of the use cases found. Each use case extracted from the literature was classified according to the relevant functionality it demonstrates. This consistent categorisation ensured comparability in the later analysis, making it possible to systematically contrast different cases and draw general insights despite variations in terminology or emphasis across sources.

In the third step, the resulting framework of DT-functionality was used as a base to revisit the selected literature to identify relevant categories of added value of DTs functionality towards the decision-making processes. In doing so, the term “value” is understood broadly, encompassing both tangible benefits such as cost savings, time reduction, and energy efficiency, and intangible advantages such as improved decision-making, enhanced transparency, or regulatory compliance.

Added value related information was extracted from the reviewed literature, focusing on reported outcomes, evaluations, and assessments to provide a deeper understanding of how value is created from the adoption of DTs. Where available, quantitative data such as percentage improvements, financial figures, or performance metrics were also listed as examples. The results were then consolidated into terms of a framework of categories of added value. Building on this, we also endeavoured to propose ways of quantifying the value generated by DTs.

We acknowledge that the chosen approach is subject to some potential limitations. Firstly, the analysis relies exclusively on published literature, which may not fully capture the latest industry developments or undocumented practical implementations. Secondly, the functional approach may overlook technical distinctions between systems, as it emphasises capabilities rather than architecture. Thirdly, the value identification is constrained by what authors report; in many cases, quantitative evaluations are limited or absent. Despite these limitations, in our view, the chosen research design enables a first systematic and focused examination of DT-related functionalities and their added value towards decision-making processes in the context of renovation.

## 4 Use Cases for Operations and Facility Management

*Operations & facility management* related activities tend to be the costliest and longest running activities across a building’s life cycle. At the same time, many facilities still lack a clear data-driven management strategy. Maintaining long-term performance and safety increasingly requires a smart, digitally integrated approach, beginning from a building’s design through to its operations and management [21]. As Wong et al. [72] highlighted, despite the availability of enabling technologies such as BIM and IoT sensors, their deployment

in facility management remains sporadic and largely confined to isolated case studies, leaving significant gaps in areas like renovation, retrofitting and predictive maintenance [72]. The latter information gap becomes particularly critical in renovation projects, where operators must manage a hybrid environment of modernised technologies and ageing infrastructure [13].

The considered literature, as discussed in more detail in [57], suggests four main types of applications for DTs for the *operations & facility management* activities: (1) they provide real-time monitoring of environmental and system parameters, such as temperature, humidity, noise levels, occupancy, and energy consumption; (2) by continuously processing live data streams, they can automatically diagnose faults and anomalies as soon as they arise. (3) they support performance simulation, enabling analyses that explore different energy-management strategies, lighting configurations, or emergency procedures before implementation; and (4) they underpin predictive maintenance by using statistical and machine-learning models to forecast equipment needs and schedule interventions before failures occur [52]. These applications can be found across five key (broad) use cases within the *operations & facility management* context.

**Predictive Maintenance** – Predictive maintenance constitutes a prominent use case, involving e.g. the utilisation of real-time sensor data on vibration, temperature, and flow to forecast equipment failures before they occur [14, 23, 68]. Predictive maintenance involves the analysis of past operational data to assess component health and forecast when and where failures or wear are likely to occur. In this context, DTs play a critical role, as they allow facility managers to continuously monitor the operational state of e.g. Heating, Ventilation, and Air Conditioning (HVAC) systems, elevators, lighting, and plumbing systems, detecting anomalies and planning interventions before performance degrades [14]. This approach avoids unplanned downtime, reduces maintenance costs, and increases equipment lifespan [23]. Using DTs, predictive maintenance is able to enhance reliability by continuously monitoring real-time parameters, such as temperature and vibration, enabling early fault detection and timely maintenance through machine learning and virtual simulation [68].

**Real-Time Monitoring and Anomaly Detection** – In addition, real-time monitoring and anomaly detection are increasingly applied to monitor structural health (e.g., bridges and façades) and environmental conditions including HVAC systems and tunnel ventilation. These approaches enable the immediate identification of operational deviations [30, 36, 53, 73, 78]. For example, as reported in Khajavi et al. [30], a wireless sensor network was installed on the facade of an office building to continuously monitor light, temperature, and humidity levels. The collected data were processed and visualised in real-time to create a DT of the facade, enabling the detection of environmental changes and potential anomalies such as occlusions caused by nearby objects or people [30].

**Performance Simulation and Analysis** – Furthermore, energy and environmental management benefits from live building data, which can drive automated control systems and enable different scenario simulations to optimise HVAC and

lighting efficiency [8,50,65]. In the paper by Borissova et al. [8], the authors report how an apartment was equipped with IoT sensors, integrated via a software platform to automate radiator valves based on time schedules and window-open events. They then constructed a 3D BIM model of the apartment and used it to simulate a year of heating loads under real-world control rules. Finally, by comparing measured energy consumption with simulation results, they demonstrate a 47% reduction in total heating use after applying DT-driven automation [8].

**Occupancy and Space-Utilisation Analytics** – Another use case is occupancy and space-utilisation analytics, which rely on technologies such as CO<sub>2</sub> sensors, smart cameras, and tracking systems like Radio Frequency Identification (RFID) or ultra-wideband (UWB). These technologies are used to monitor how people move through and use spaces within a building. The resulting data helps forecast where and when heating, cooling, or lighting will be needed, thereby supporting more efficient space planning [40,61,71]. Seghezzi et al. [61] conducted a study to calibrate and assess a camera-based IoT sensor system for occupancy monitoring, as part of developing an occupancy-oriented DT for facility management. Their work involved test campaigns in a university office building to identify data collection issues, optimise sensor placement and orientation using BIM-supported post-occupancy evaluations, and evaluate data quality. The study demonstrated that with proper calibration and iterative testing, such systems can effectively monitor real-time space usage, enabling improved planning of cleaning services and space utilisation [61].

**Safety Risk Management** – Safety risk management involves risk-driven management of safety of a building and its “users”. The associated activities can be supported by DTs that integrate sensor, vision, and positioning data to detect on-site hazards, such as fall risks on ladders or scaffolds, unsafe equipment use, or the early stages of fire spread. These systems can generate timely alerts and evacuation paths to enhance on-site safety [15,35,41]. In Cheng et al. [15], for instance, the authors built a BIM-based intelligent fire prevention and disaster relief system by embedding Bluetooth-enabled smoke and temperature sensors (and RFID positioning tags) into a 3D DT of a completed building. Continuous environmental and locational data feed the virtual model, where computer-vision algorithms detect hazards and a graph-search engine dynamically updates the safest evacuation routes, with turn-by-turn guidance delivered to occupants’ and responders’ devices, linking real-time sensing, simulation, and on-site action to improve situational awareness and response times [15]. As DT technologies evolve, they are increasingly being integrated with existing building management systems and facility information models, enhancing their utility for operations teams [22]. Despite challenges such as legacy-system interoperability and sensor deployment costs, DTs are increasingly recognised as essential for sustainable, efficient, and intelligent operations and facility management [31,43].

## 5 Value Identification and Quantification

This section aims to address the current gap in assessing the added value of DTs. Despite increasing interest, organisations continue to encounter significant difficulties in realising and articulating clear benefits from DTs. As mentioned in the introduction, Trauer et al. [66] also stressed the need to better identify the added value of DTs. More specifically, they saw as main challenges: (1) “*Identifying clear and valid value propositions associated with the DT solution*”, (2) “*Focus on when a DT can add which value ... it will be crucial to have a systematic approach to assess when the implementation of a DT really pays out and when it does not*”, and (3) “*How the data can be used to create added value for maintenance and development, while ensuring that the costs and benefits are in proportion*”. Building on this perspective, Perno et al. [51] conducted a systematic literature review to identify the key enablers and barriers to implementing DTs in the process industry. The authors of said paper, also emphasise that across several of the reviewed studies, a recurrent concern is the difficulty of identifying and articulating the value of DTs. They also observe how this struggle is particularly evident in organisational settings where the novelty and complexity of DT technologies make it challenging to formulate clear value propositions or quantify potential returns.

To gain a better understanding of the value of DTs in a renovation context, we suggest to categorise the potential added value DTs in two main categories: *direct added value* and *indirect added value*.

**Direct Added Value** – DT technology delivers several direct economic benefits in building renovation projects, primarily through improved efficiency and resource optimisation. One major form of potential direct added value, is improvement of energy efficiency and associated cost savings. As discussed in the previous section, integrating real-time sensor data with building models, DTs enable fine-tuned control of e.g. HVAC, lighting, and other systems to match occupancy patterns. This optimises energy use and cuts utility costs. Studies report significant energy reductions – for example, one implementation [34] achieved about 17% lower energy consumption after deploying a building DT for optimised controls. In turn, lowering energy use directly reduces operating costs and even carbon emissions, helping meet sustainability goals. DTs also allow stakeholders to simulate retrofitting scenarios virtually before physical changes are made. By testing renovation options virtually, owners can identify the most cost-effective energy conservation measures and avoid expensive trial-and-error during construction [13]. This data-driven planning shortens project timelines and prevents rework, directly translating to capital cost savings [5].

Another source of direct added value comes from maintenance and operational cost reduction [77]. By leveraging predictive maintenance, DTs shift building management from reactive fixes to proactive upkeep, helping avoid costly emergency repairs. Researchers highlight predictive maintenance as a major benefit of DT-enabled facility management, closely tied to maintenance cost savings [13]. In [23], the authors report on a hospital case study where the use

of a DT featuring automated fault diagnostics resulted in over 10% fewer facility faults and repairs, yielding a substantial maintenance cost avoidance and improved stakeholder satisfaction. Industry surveys also show that continuously monitoring asset conditions via a DT helps anticipate maintenance needs, reducing operational expenses and streamlining management workflows. In summary, by streamlining operations, DTs reduce energy and maintenance costs, generating significant savings and a strong business case for their integration into renovation and building management [13].

**Indirect Value Streams** – Beyond these immediate cost and energy impacts, DTs can create added value in an indirect way as well, involving long-term positive impacts on performance and sustainability of a building portfolio.

One crucial indirect benefit is improved reliability and uptime of building systems. With predictive insights from a DT, facility managers can address issues before they escalate, minimising unplanned downtime of critical equipment [67]. For example, a DT continuously monitoring a building's mechanical systems can detect anomalous behaviour (such as an HVAC component deviating from normal parameters) and alert staff to intervene early. This proactive approach ensures that building services (heating, cooling, elevators, etc.) experience fewer unexpected outages, meaning less disruption to occupants and business operations. Although the monetary value of avoided downtime can be hard to quantify, it is significant – reduced system outages protect revenue in commercial buildings and maintain tenant comfort, thereby safeguarding the building's value proposition in an indirect but important way. By enabling predictive maintenance strategies, DTs help shift maintenance to off-peak times or planned intervals, which bolsters reliability and keeps facilities running smoothly [6].

DTs also contribute to extended lifespans of buildings, and add value by enabling proactive, data-driven management optimisation. By using a continuous flow of sensor data, and simulation-based behaviour modelling, DTs support early fault detection and predictive maintenance, preventing minor defects from escalating into catastrophic failures that shorten equipment life, as demonstrated in sectors such as mining where AI-driven monitoring has reduced unplanned downtime and prolonged asset life cycles [32, 58]. This proactive approach defers capital expenditures by reducing the need for frequent large-scale replacements and lowers total cost of ownership. In renovation contexts, DTs also indirectly create value by enhancing sustainability and regulatory compliance: optimised building operations reduce energy consumption and CO<sub>2</sub> emissions, support alignment with green building standards, and enable predictive modelling of energy use and occupant behaviour to improve efficiency [13, 62, 75]. Advanced platforms further provide continuous sustainability dashboards and scenario-based simulations – such as assessing the impact of solar panels or insulation upgrades without physical intervention – supporting informed cost-benefit analyses for retrofitting and decarbonisation, while strengthening organisational reputation and future-proofing assets against evolving low-carbon regulatory and market demands [47, 69].

Quantifying the, direct or indirect, added value of a DT involves some form of economic framework. As part of our literature study, several frameworks were reviewed to support the quantification of DT value. Among these, *life cycle cost analysis* (LCCA) and *return on investment analysis* (RoI) stand out as primary evaluation methods.

**Life Cycle Cost Analysis** – To achieve sustainable construction requires decision-making frameworks that account not only for economic performance but also for environmental and social impacts throughout a building’s entire life cycle [2]. LCCA has emerged as an economic evaluation method that considers all costs of owning, operating, maintaining, and disposing of a building or system over its entire lifespan, whilst it enables stakeholders to compare the costs and sustainability implications of alternative project designs [2,3].

Even though the use of DT technology is increasingly integrated into LCCA, its own value remains largely unquantified as research mainly focuses on using DTs to enhance LCCA, rather than applying LCCA to measure the value delivered by the twins themselves [17]. Nevertheless, [9] on DTs for light rail infrastructures, LCCA was applied alongside Life Cycle Assessment (LCA) within a BIM-based environment to holistically assess both environmental and economic impacts across the infrastructure life cycle. The authors implemented LCCA to convert costs from various project phases into present values, thereby enabling better-informed decisions during early-stage design. The study found that DT integration enabled parametric sensitivity testing (e.g., varying grout volumes), which uncovered cost-intensive components such as unrecyclable bitumen and grout. Importantly, the authors emphasised that such insights allow for real-time design adjustments in DT environments, which significantly enhances the sustainable value of infrastructure investments. This substantiates their claim that DT-aided LCCA facilitates proactive cost optimisation and supports sustainable development decisions throughout the project life cycle [9].

**Return on Investment Analysis** – Return on Investment (RoI) is a widely used metric that helps evaluate the efficiency and effectiveness of an investment by comparing the financial return to the associated costs. Fundamentally, RoI is defined as the ratio between the net gain from an investment and its cost, often expressed as a percentage, providing a standardised way to assess profitability across different initiatives and sectors [11]. It originated as a financial tool grounded in rigorous accounting principles and has since become a ubiquitous metric in both the private and public sectors due to its simplicity, clarity, and ease of interpretation [64].

The assessment of RoI regarding DT applications varies across different sectors and is influenced by context-specific financial, operational, and technological considerations, as shown in the following subsection. In the manufacturing sector, Malik [38] proposes a structured, simulation-based framework that explicitly connects technological investments in DTs to financial outcomes. Similarly, Banyai and Kovács [7] examine DTs in the context of job-shop manufacturing. Their research introduces a simulation-supported methodology that links productivity metrics such as lead time and capacity utilisation to finan-

cial indicators. In a different industrial context, Deshpande and Deshpande [16] explore the application of DTs in the printing and packaging industry, where dynamic production schedules, custom orders, and regulatory compliance drive digital innovation.

Also in high-tech and capital-intensive domains like aerospace and defence, Malone [39] emphasises that RoI estimation for DTs is deeply influenced by model fidelity, development effort, and system complexity. At the same time, the authors also caution that traditional RoI calculations often overlook the scalability and integration costs of DT systems, especially in multi-stakeholder environments like defence procurement [39].

## 6 Conclusion

In this paper, we investigated how DTs support decision-making and add value in building renovation, focusing on *operations & facility management*, and how this value can be assessed and, where possible, quantified. We highlighted key DT use cases, explicitly linking functionalities to renovation phases, categories of added value, and quantification strategies, drawing on literature and economic frameworks. By framing DTs in terms of decision-support value rather than technical capability alone, the study provides practical guidance for evaluating and prioritising DT investments. Future work should broaden and deepen the evidence base for the added value of DTs by conducting long-term, comparative studies across diverse renovation projects, helping establish robust, actionable metrics for decision-makers in the construction sector.

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