A digital twin implementation strategy for predictive maintenance in facility management

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Abstract

Purpose – Digital twin (DT) technology holds significant promise for transforming facility management (FM) by enabling real-time asset monitoring, early fault detection and data-driven decision-making for predictive maintenance (PdM). While PdM uses historical and real-time data to anticipate equipment failures, DT offers dynamic virtual replicas of physical assets for continuous performance optimization. This study aims to examine the integration of DT and building information modeling to support PdM in building facilities, aiming to address inefficiencies inherent in traditional reactive maintenance approaches. The research explores key questions around the main challenges and benefits of deploying DT for PdM, the effectiveness of DT in enhancing FM processes and sustainability and the critical components needed for a practical DT implementation strategy.

Design/methodology/approach – A qualitative approach was adopted, combining a systematic literature review with semistructured interviews with industry professionals. Thematic analysis was used to synthesize the results.

Findings – The results demonstrate DT's potential to improve maintenance through enhanced decision-making, greater operational efficiency and stronger predictive capabilities. However, significant challenges were identified, including high implementation costs, data integration challenges, lack of standardization, organizational resistance and skill gaps. The findings highlight the significance of aligning people, processes and technology to enhance the impact of DT.

Practical implications – The research offers actionable insights for facility managers and policymakers aiming to implement DT-driven PdM, ultimately supporting the development of smarter and more sustainable built environments.

Originality/value – This study proposes a structured strategy comprising seven key elements to facilitate DT adoption in FM: (1) needs assessment, (2) incremental deployment, (3) structured data management, (4) seamless system integration, (5) organizational anchoring, (6) standardization protocols and (7) a long-term vision.

Keywords Digital twin, Facility management, Predictive maintenance, Internet of Things, Building lifecycle management, Standardization, Interoperability, Common data environment, Maturity level, Practical strategy

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1. Introduction

Facility management (FM) is increasingly influenced by digitalization, with a growing interest in data-driven methods to improve operational efficiency, reduce costs and extend the lifespan of building assets. One of the most promising developments in this context is digital twin (DT) technology, which enables the creation of a dynamic virtual representation of physical assets (Ghansah, 2025; Yitmen *et al.*, 2025). When integrated with building information modeling (BIM) and real-time sensor data, DT can provide continuous insights into building performance, facilitating proactive and predictive maintenance (PdM) (Desogus *et al.*, 2021; Shuhaimi *et al.*, 2024). DT-enhanced PdM is claimed to improve building facility efficiency and reliability by replacing traditional "fail-and-fix" approaches with "predict-and-prevent" strategies (Gispert *et al.*, 2025). While the potential of DT is widely acknowledged in both academia and industry, the degree of adoption varies significantly between organizations. Some actors have implemented advanced DT systems, whereas others lack even the basic prerequisites, such as digital models or sensor infrastructure. This inconsistency presents a major challenge, as the absence of standards, technical integration and strategic direction hinders effective use of DT in building operations (AlBalkhy *et al.*, 2024; El-Din *et al.*, 2022; Godager, 2024). Moreover, there is currently no established practical guide or manual to support organizations in implementing DT for FM (Hauashdh *et al.*, 2024; De Rubeis *et al.*, 2023). Against this backdrop, the research problem addressed in this study is the lack of practical, structured strategies for implementing DT in building maintenance, despite their growing relevance. The purpose of the study is to explore how DT can be used to enhance PdM and improve decision-making in FM and to identify key elements for a practical implementation strategy. This study focuses on technical building maintenance during the operational phase, where BIM models are combined with real-time data to support data-driven decision-making.

The topic is investigated through a systematic literature review and semistructured interviews conducted with industry professionals. The study is guided by the following research questions (*RQs*):

RQ1. What are the main benefits and challenges of implementing digital twins for technical building maintenance within BIM-supported FM processes?

RQ2. What are the key elements of a practical strategy for implementing digital twins in building maintenance?

Together, these questions aim to clarify the role of DT in advancing PdM, improving decision-making and supporting more sustainable and efficient FM. The paper is structured as follows:

1. Section 2 provides a theoretical background on DT, PdM in building facilities, adoption of drivers and benefits for implementation of DT in FM, implementation of challenges of DT in FM, standards for implementation of DT, the absence of a comprehensive manual for DT implementation in FM and organizational and technical preconditions for a practical DT strategy.
2. Section 3 comprises a comprehensive explanation of the methodology involving a systematic literature review and semistructured interviews with industry professionals.
3. Section 4 presents the results of the qualitative analysis. The main benefits and challenges of implementing DT for technical building maintenance within BIM-supported FM processes, the key elements of a practical strategy for implementing

DT in building maintenance, methodological reflections and prospective areas for further study are discussed in Section 5.

(4) The manuscript is concluded in Section 6.

2. Theoretical background

2.1 Digital twins

A DT is a virtual model of a physical entity, such as a product, asset, component, process or system, that enables real-time data exchange and accurately reflects the state, behavior and processes of its physical counterpart throughout its lifecycle (AlBalkhy *et al.*, 2024; Ghansah, 2025; Gispert *et al.*, 2025; Madubuike *et al.*, 2022). This bi-directional connection between the physical and digital environments supports predictive decisions and distinguishes DT from static BIM models by allowing real-time updates and simulations (Ghansah, 2025; El-Din *et al.*, 2022). Technologically, DT relies on the integration of sensors, control systems and data algorithms that continuously synchronize hardware (the physical object) with software (the digital model), enabling the DT to function as the "intelligent brain" of the asset (Li *et al.*, 2023; Madubuike *et al.*, 2022; Gispert *et al.*, 2025). In the FM sector, DT is considered an advancement of BIM and is used to monitor assets in real time and enable PdM through dynamic data modeling (El-Din *et al.*, 2022; Madubuike *et al.*, 2022).

2.2 Predictive maintenance in building facilities

Although many facilities are already equipped with online monitoring systems, maintenance practices often remain reactive, relying on manual inspections that risk delayed interventions (Li *et al.*, 2023; Desogus *et al.*, 2021). DT, when integrated with Internet of Things (IoT) sensors, enables real-time monitoring of conditions such as temperature, humidity and energy use, allowing facility managers to predict maintenance needs and make informed decisions (Li *et al.*, 2023; Desogus *et al.*, 2021). Several researchers have proposed PdM frameworks based on DT, BIM and IoT to improve fault detection, maintenance planning and energy performance (Shalabi and Turkan, 2019; Villa *et al.*, 2021; Cheng *et al.*, 2020; Madubuike *et al.*, 2022; El-Din *et al.*, 2022). Machine learning (ML) and big data have further enhanced these capabilities by supporting predictive analysis (Bouabdallaoui *et al.*, 2021). DT supports PdM and smart monitoring by enabling insights into asset health, remaining useful life and potential failures, helping to avoid unplanned downtime (Madubuike *et al.*, 2022; Shuhaimi *et al.*, 2024). Predictive strategies enabled by DT reduce disruptions and improve operational continuity. DT also improves real-time diagnostics and visualization across spaces, supporting energy optimization and remote control of environmental conditions (De Rubeis *et al.*, 2023). Intelligent control systems, integrated with DT and based on factors like occupancy, lighting and heating, ventilation and air conditioning (HVAC) – can lead to energy savings of up to 30% (Li *et al.*, 2023). In summary, DT-enabled PdM increases operational efficiency, reduces energy use and extends asset lifespan through continuous, intelligent monitoring (Li *et al.*, 2023; Madubuike *et al.*, 2022; El-Din *et al.*, 2022; Shuhaimi *et al.*, 2024).

2.2.1 Focus on key building assets for digitalization in predictive maintenance. In FM, the range of assets requiring maintenance and monitoring varies widely – from structural components to complex technical systems. However, not all assets present equal potential or urgency for digitalization within a DT framework. To establish a more targeted and efficient DT implementation strategy, this study focuses on a subset of critical technical assets that significantly influence operational performance, maintenance frequency and lifecycle cost. These include HVAC systems, electrical distribution and lighting networks, plumbing and water systems, façade elements (including cladding and window systems) and elevator and safety systems. These components are prioritized because they represent the highest maintenance expenditures and most frequent causes of operational disruptions in buildings (Desogus *et al.*, 2021; Li *et al.*, 2023; Yoon, 2024).

Digitalization of these asset types enables predictive analytics through continuous data acquisition from sensors and control systems, thereby supporting early fault detection and optimization of maintenance scheduling. For instance, HVAC and energy systems are often equipped with IoT-enabled meters and controllers that allow real-time tracking of efficiency, while façade and envelope components can benefit from environmental sensors for monitoring moisture intrusion, thermal performance or surface degradation. Similarly, digital models of elevators and safety systems can support automated diagnostics and failure prediction using ML algorithms. By concentrating on these core assets, this research ensures that DT-enabled PdM efforts are both technically feasible and operationally impactful, providing a replicable framework for prioritizing asset digitalization in FM.

2.3 Adoption of drivers and benefits for the implementation of digital twin in facility management

The integration of DT technology with BIM and IoT platforms plays a significant role in improving asset management and operational efficiency. By enabling real-time monitoring and PdM, DT allows facility managers to make timely data-driven decisions that proactively address maintenance needs and extend the lifespan of building components (El-Din *et al.*, 2022; Shuhaimi *et al.*, 2024). Several drivers have been identified in the literature as contributing to the adoption of DT in FM, including regulatory compliance, technological advancements and the potential for lifecycle efficiency (Shuhaimi *et al.*, 2024). These drivers, along with associated benefits and enabling technologies, are summarized in Table 1.

2.4 Implementation challenges of digital twin in facility management

Despite these benefits, DT implementation in FM encounters significant barriers. Shuhaimi *et al.* (2024) emphasize issues such as high costs associated with deploying IoT sensors, data integration complexities and the need for system standardization. Gispert *et al.* (2025) identified several critical challenges in implementing PdM systems, including:

(1) incompatibility issues between sensor data structures from different providers;
(2) the complexity of maintaining accurate asset information models;
(3) difficulties in data restructuring following building refurbishments; and
(4) the challenge of balancing sensor quantity requirements with the costs of data-point collection infrastructure.

Yoon (2024) emphasizes stakeholder engagement and organizational readiness, especially in legacy systems. The absence of standardized frameworks for interoperability between DT and BIM systems remains a major barrier (Abdelalim *et al.*, 2024). Similarly, Cespedes-Cubides and Jradi (2024) underline the lack of integrated digital data, particularly in older buildings, necessitating improved methods and standards for data fusion. Furthermore, the fragmented nature of the AEC industry complicates DT adoption, with diverse stakeholders often resisting collaboration and relying on traditional practices (AlBalkhy *et al.*, 2024). Limited understanding of DT concepts and challenges related to data management further underscores the need for robust data strategies. Organizational issues such as unclear role definitions, poor scheduling, reliance on paper-based records and low-bid contractor selection also hinder performance and sustainability efforts (Hauashdh *et al.*, 2024).

Table 1. Summary of key drivers, benefits and technologies related to DT adoption in FM

Drivers	Benefit	Description	References
PdM and sustainability	Enhance sustainability and FM	By enabling real-time monitoring and ML-based optimization of energy use, conservation and occupant comfort	AlBalkhy *et al.*, 2024; Cespedes-Cubides and Jradi, 2024
Cost reduction and improved energy efficiency	Lower operational cost and enhanced energy performance	By optimizing systems like lighting and HVAC based on occupancy patterns and enabling intelligent control systems, energy use can be reduced by up to 30%	Cespedes-Cubides and Jradi, 2024; Yoon, 2024; Li *et al.*, 2023
Improved safety risk prediction	Enhanced safety risk management	By enabling safer design, continuous monitoring and predictive risk analysis, particularly in complex systems and large-scale projects	AlBalkhy *et al.*, 2024
Operational efficiency and decision-making	Increased system performance and extended	By integrating virtual models with real-time data to enable continuous monitoring, reduce downtime and support smarter decisions	Shuhaimi *et al.*, 2024
Technological advancements and integration	Improve asset management, communication and performance	By enabling anomaly detection, retrofit simulations and real-time monitoring, while integrating BIM and IoT to enhance collaboration and efficiency	Cespedes-Cubides and Jradi, 2024; Shuhaimi *et al.*, 2024

Source(s): Authors' own work

These are compounded by fragmented responsibilities, manual overrides and misaligned incentives that obstruct lifecycle-based, optimized decision-making (Hunhevicz *et al.*, 2022). Table 2 summarizes the existing research on DT implementation for PdM in FM.

2.5 Standards for implementation of digital twins

Standardization is essential for implementing DT in the AECO industry, particularly to ensure interoperability, data quality and a shared understanding of system interfaces (Madubuike *et al.*, 2022; El-Din *et al.*, 2022). However, the lack of standards for device communication and data integration remains a key barrier, contributing to poor performance and perceptions of DT as complex and difficult to adopt (Godager, 2024). Existing standards like International Organization for Standardization (ISO) 19650 offer a solid foundation for structured data management using BIM and promote the use of common data environments (CDEs), but they provide limited practical guidance for DT integration (ISO, 2019; El-Din *et al.*, 2022). To support the effective implementation of DT, future frameworks must go beyond traditional BIM and incorporate real-time IoT integration, automated data extraction and lifecycle-wide standardization (Cespedes-Cubides and Jradi, 2024). This is particularly critical for retrofitting older buildings and ensuring consistent data flows across systems and

Table 2. Summary of existing research on digital twin implementation for predictive maintenance in facility management

References	Focus area	Methodology/approach	Key findings/contributions	Relevance to predictive maintenance (PdM) in FM
Li *et al.* (2023)	Integration of IoT-enabled DTs for predictive maintenance in HVAC systems	Case study and simulation-based validation	Demonstrated energy savings up to 30% through real-time monitoring and predictive analytics	Showed tangible performance and cost benefits of DT-driven PdM in building systems
Desogus *et al.* (2021)	DT-based predictive models for maintenance decision support	Conceptual framework and FM system integration	Highlighted data-driven decision-making and continuous monitoring for early fault detection	Validated DT's potential to reduce unplanned downtime in FM
El-Din *et al.* (2022)	BIM-IoT integration for maintenance management	Empirical study using BIM-based digital models	Improved interoperability and data visualization between maintenance and asset systems	Enhanced PdM workflows via automated data capture and visualization
Shuhaimi *et al.* (2024)	AI-augmented DT systems for predictive maintenance	Quantitative model evaluation	Proposed AI algorithms for anomaly detection using DT data streams	Advanced predictive capability through intelligent analytics
Gispert *et al.* (2025)	Transition from reactive to predictive maintenance using DT	Literature synthesis and framework development	Introduced "predict-and-prevent" paradigm leveraging DT data integration	Emphasized long-term shift toward proactive facility operations
Madubuike *et al.* (2022)	DT integration in facility management for maintenance efficiency	Mixed-method approach (survey + case analysis)	Reported improved decision-making, efficiency and reliability in FM	Demonstrated practical DT benefits in FM contexts through PdM use cases
Cespedes-Cubides and Jradi (2024)	Energy management and PdM through DT platforms	Simulation and experimental validation	Validated DT-driven optimization of energy performance and maintenance scheduling	Linked PdM with sustainability goals in building operations
AlBalkhy *et al.* (2024)	Barriers to DT adoption in FM	Literature review	Identified high implementation costs, lack of expertise and limited standardization	Highlighted critical challenges hindering PdM realization
Hauashdh *et al.* (2024)	Organizational readiness for DT-based FM	Qualitative interviews with FM stakeholders	Found that digital maturity and cultural acceptance are key for DT success	Emphasized the human and organizational dimension of PdM adoption

(*continued*)

Table 2. Continued

References	Focus area	Methodology/approach	Key findings/contributions	Relevance to predictive maintenance (PdM) in FM
Godager (2024)	Data management frameworks for DT in FM	Theoretical framework proposal	Proposed standardized data handling aligned with ISO 19650	Provided foundation for structured data critical for PdM performance
De Rubeis *et al.* (2023)	Practical implementation strategies for DTs in buildings	Comparative case study	Noted lack of standardized practical guidance and varying DT definitions	Addressed implementation barriers to PdM-oriented DT systems

Source(s): Authors' own work

project stages. Advancing such standards will be vital for enabling broader adoption of DT and improving overall system performance.

2.6 The absence of a comprehensive manual for digital twin implementation in facility management

Despite growing interest in DT technology, the literature consistently identifies a significant research gap: the absence of a comprehensive, practical manual for implementing DT in the FM sector. A review of over 1,000 articles found no widely accepted guidance on how DT should be applied in practice (Hauashdh *et al.*, 2024). While benefits such as real-time monitoring, PdM and improved decision-making are well acknowledged, standardized procedures and frameworks remain limited (Madubuike *et al.*, 2022). Although some studies offer partial contributions, such as workflows, tool recommendations and standardization efforts (De Rubeis *et al.*, 2023; El-Din *et al.*, 2022). These approaches are fragmented and lack broad applicability. The lack of definitional consensus further complicates adoption. Overall, the absence of a unified, actionable strategy reinforces the need for this study and its aim to contribute a practically grounded implementation framework.

2.7 Organizational and technical preconditions for a practical digital twin strategy

Godager (2024) argues that implementing DT in building maintenance requires addressing both human and technical challenges. A practical strategy must consider these dimensions to succeed.

2.7.1 Organizational aspects (human and process-related). The building sector is often characterized by fragmented information flows and resistance to digital change (Godager, 2024). For DT implementation to succeed, it must align with business strategy and be supported by lifecycle-based information strategies. Central to this are the definitions of organizational information requirement (OIR) and asset information requirement (AIR), which clarify what data is needed and why (Godager, 2024; El-Din *et al.*, 2022). Key enablers include clear roles, early stakeholder engagement, user involvement and digital competence, along with a shift in organizational culture. Frameworks like ISO 19650 and structured environments such as CDE support collaboration and information consistency across the lifecycle (Godager, 2024; El-Din *et al.*, 2022).

2.7.2 Technical aspects. On the technical side, DT systems require integration of core technologies, including BIM for digital models, IoT sensors for real-time data and platforms for data processing and visualization (Godager, 2024; El-Din *et al.*, 2022; Desogus *et al.*, 2021). Artificial intelligence (AI) and ML further support PdM detecting anomalies and improving decision-making (Godager, 2024). However, system interoperability and consistent modeling practices remain challenges, reinforcing the need for standardized CDEs (Godager, 2024; El-Din *et al.*, 2022). A strong technical foundation includes a reliable BIM model, integrated sensor infrastructure and tools to analyze and visualize data to support operational decisions.

2.7.3 Key elements of a practical strategy for implementation. A successful DT implementation strategy must combine organizational and technical dimensions (Godager, 2024). Strategically, it should begin with a clear definition of purpose and value, supported by lifecycle-based information strategies and defined requirements such as OIR, AIR and levels of information need (LOIN) (Godager, 2024; El-Din *et al.*, 2022). Early stakeholder engagement, defined roles, competence development and cultural readiness are essential (Godager, 2024). Technically, the strategy requires a high-quality BIM model, integration of IoT sensors for real-time and historical data and a standardized CDE to ensure interoperability (Godager, 2024; El-Din *et al.*, 2022; Desogus *et al.*, 2021). Data should be analyzed and visualized through dedicated tools to enable informed decision-making (Godager, 2024; El-Din *et al.*, 2022).

2.7.4 Summary. A successful strategy for implementing DT in building maintenance must address both organizational and technical dimensions. It should begin with clear, business- and user-driven objectives, supported by lifecycle-based information strategies and defined information needs (OIR, AIR and LOIN) (Godager, 2024; El-Din *et al.*, 2022). Key organizational enablers include early stakeholder engagement, defined roles, digital competence and cultural readiness. Technically, the strategy must ensure a reliable BIM foundation, integration of sensor technologies, standardized data environments (CDEs) and tools for processing and visualizing data (Godager, 2024; El-Din *et al.*, 2022; Desogus *et al.*, 2021). Strategic alignment across people, processes and technology is essential to achieve long-term value and operational success.

2.8 Summary of research gaps

A critical analysis of the reviewed literature reveals that while the integration of DT technologies within FM has been increasingly recognized, several conceptual and practical gaps persist. Most existing studies have focused on the technical development of DT architectures or on specific PdM use cases (e.g. Li *et al.*, 2023; Desogus *et al.*, 2021; Shuhaimi *et al.*, 2024), often overlooking the organizational and managerial preconditions necessary for successful adoption. This limitation is particularly evident in the fragmented understanding of how data interoperability, standardization and organizational culture influence the transition from static BIM models to dynamic DT ecosystems capable of supporting real-time maintenance decisions.

Furthermore, despite the growing availability of sensor and IoT data, there remains a lack of holistic frameworks that explain how technical capabilities and human factors co-evolve during DT implementation. Studies tend to address isolated aspects – such as data analytics (Yoon, 2024), interoperability (Cespedes-Cubides and Jradi, 2024) or lifecycle assessment (El-Din *et al.*, 2022) – without connecting these elements to the broader sociotechnical dynamics of FM organizations. Similarly, while PdM has been identified as a primary benefit of DT adoption, empirical research on how organizations operationalize and sustain these benefits across lifecycle stages is scarce. This disconnect highlights a gap between theoretical potential and practical realization of DTs in FM environments.

Analyzing the literature through this lens underscores the need for a comprehensive, practice-oriented investigation that addresses both technological integration and organizational maturity. The synthesis of previous findings indicates that successful DT implementation requires not only robust data structures and system interoperability but also clear alignment with organizational strategies, competence development and long-term value realization mechanisms. These insights collectively inform the formulation of this study's research questions, which aim to explore the benefits and challenges associated with DT adoption for technical building maintenance and the key elements of a practical strategy that enables effective implementation within BIM-supported FM processes.

3. Research method

This study adopts a qualitative, explorative approach suitable for investigating complex and emerging phenomena, such as DT implementation in FM. Through a combination of systematic literature review and semistructured interviews with industry professionals, the study aims to identify challenges, explore current practices and inform the development of a practical implementation strategy. The collected data were analyzed using thematic analysis to identify key patterns and insights.

3.1 Literature review

A systematic literature review was conducted to explore DT applications in FM, with a focus on challenges, efficiencies and sensor integration. The review included studies on BIM, IoT and data-driven maintenance, highlighting the lack of standards for DT implementation in new construction. Targeted searches were performed in Scopus and ScienceDirect using specific keywords and filters:

Keywords: “digital twin,” “building maintenance,” “sensor technology” and “facility management”.

Search limitations: To maintain rigor, with focus on peer-reviewed articles published in English between 2020 and 2024.

Inclusion criteria: Peer-reviewed studies that directly discuss DT technology in building maintenance, covering aspects of sensor integration and operational efficiency.

Exclusion criteria: Articles unrelated to construction and FM or not aligned with our *RQs*.

The search process progressively filtered results through title, abstract and full-text reviews. Quotation marks were used around keywords to reduce irrelevant articles and better align the results with the research focus on DT in building maintenance. This process is outlined in Table 3. To ensure transparency, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were followed, and the flow diagram, as shown in Figure 1, was used to visually document the selection stages from identification to final inclusion.

3.2 Interview study

Semistructured interviews were conducted with professionals in building maintenance, DT, BIM and IoT to explore industry needs, challenges and practices related to DT implementation in new construction. This method allowed flexibility while following predefined research themes. The interviews, divided into two respondent groups as seen in Table 4, aimed to assess DT applicability and inform the development of a practical implementation strategy. The respondents were selected through purposive sampling to gather relevant perspectives from professionals in building maintenance and digitalization. All respondents were based in Sweden, providing a geographically focused understanding of the local industry context and digital transformation landscape. The selection included both public and private actors with varying levels of digital maturity. This strengthens the credibility of the findings and is further addressed in the validity section.

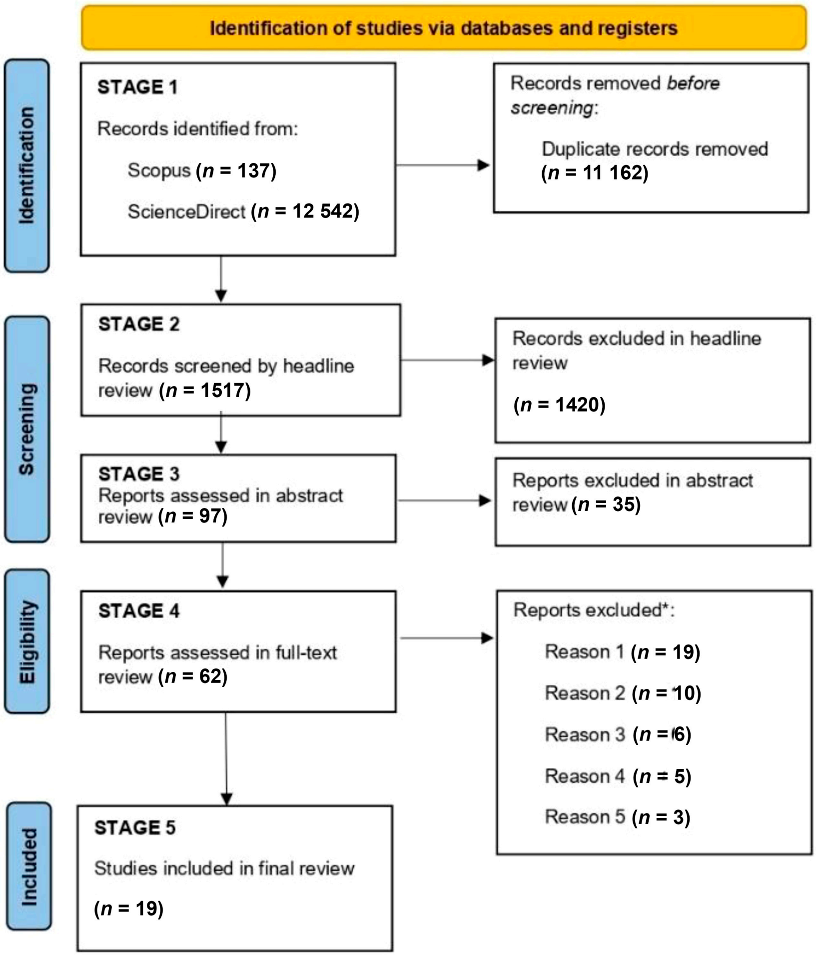
The study’s sample comprised nine professionals (R1–R9) representing public, private, municipal and consulting organizations in Sweden, as shown in Table 5. Their expertise in FM, BIM, IoT and digital transformation ensured that the data captured multiple perspectives relevant to DT implementation in building maintenance. The number of respondents aligns with qualitative research standards emphasizing analytical depth over statistical breadth, and thematic saturation was achieved after eight interviews. The sample’s diversity – spanning various roles, organizational types and digital maturity levels – enhances the transferability of findings within the Swedish FM context. While purposive sampling may introduce bias toward digitally active organizations, this limitation was mitigated by including actors at different maturity stages and validating patterns across participants. This approach strengthens the study’s credibility and ensures that the findings reflect a balanced view of DT adoption dynamics in practice.

Table 5 provides an overview of the respondents’ professional backgrounds, including their experience, roles, expertise and company types, which helps contextualize the insights collected in the interviews.

Table 3. Search strategy, including keywords, database and the search date

Search strategy	Search database	Search results	Search field	Search date
“digital twin” AND “building maintenance”	Scopus	12	TITLE-ABS-KEY	November 05, 2024
“sensor technology” AND “digital twin” AND “sensor data”	Scopus	4	TITLE-ABS-KEY	November 06, 2024
“implementation challenges” AND “digital twin” AND “facility management”	Scopus	2	TITLE-ABS-KEY	November 06, 2024
“facility management” AND “digital twin” AND “implementation” OR “adaption” AND “manual”	Scopus	119	TITLE-ABS-KEY	January 20, 2025
“digital twin” AND “building maintenance”	ScienceDirect	99	TITLE-ABS-KEY	November 05, 2024
“sensor technology” AND “digital twin” AND “sensor data”	ScienceDirect	301	TITLE-ABS-KEY	November 06, 2024
“implementation challenges” AND “digital twin” AND “facility management”	ScienceDirect	11	TITLE-ABS-KEY	November 06, 2024
“facility management” AND “digital twin” AND “implementation” OR “adaption” AND “manual”	ScienceDirect	12 131	TITLE-ABS-KEY	January 20, 2025

Source(s): Authors’ own work



- Reason 1: Not directly related to Digital Twin or building maintenance **(*n* = 19)**
- Reason 2: Lacked primary data or substantial analysis **(*n* = 10)**
- Reason 3: Duplicated findings from other included studies **(*n* = 6)**
- Reason 4: Irrelevant focus on unrelated aspects **(*n* = 5)**
- Reason 5: Language limitations **(*n* = 3)**

Figure 1. Paper selection process (PRISMA flow diagram)
Source: Authors’ own work

Table 4. Interview sections

Section	Purpose	Description
Section 1.0: FM	To understand current maintenance processes, identify problems and needs for implementing DT in FM	Interviews with individuals responsible for maintenance within FM to identify needs and solutions
Section 2.0: DT specialists	To gain technical insights, DT, their usage and implementation and identify success factors and challenges	Interviews with experts on DT to gather their views on implementation and challenges in projects

Source(s): Authors' own work

3.3 Data analysis

To interpret the interview data, thematic analysis will be used to identify and report patterns within the responses (Braun and Clarke, 2006). This approach enables a deeper understanding of interviewees' experiences and needs regarding DT implementation. The process includes five steps:

(1) transcribing and familiarizing with the data;

(2) coding key segments;

(3) grouping codes into themes;

(4) refining themes for relevance; and

(5) presenting findings supported by quotes. This method aims to extract practical insights for DT applications in building maintenance.

3.3.1 Sample context and coding workflow. The empirical material comprised nine semistructured interviews ($n = 9$) with professionals representing public, private, municipal and consulting organizations within Sweden's FM and building maintenance sector. This national context reflects Sweden's progressive agenda toward digitalization in the built environment, characterized by the widespread integration of BIM, IoT and sustainability-driven asset management practices. Respondents were selected through purposive sampling to ensure relevance and diversity, focusing on individuals with direct responsibility for digital transformation, technical maintenance and data-driven FM. The sampling strategy thus captured both strategic decision-makers and operational experts, enabling a comprehensive understanding of organizational readiness for DT implementation.

The interviews were transcribed *verbatim* and analyzed manually using thematic analysis (Braun and Clarke, 2006). Initial codes were generated from recurring concepts linked to digital maturity, data management and organizational capacity. To ensure reliability, two researchers jointly coded three transcripts during the initial phase, comparing interpretations and refining the coding framework. The remaining transcripts were coded independently by the lead researcher using the agreed framework. Differences in interpretation were discussed until consensus was achieved. Member checking was conducted with three participants to confirm that the thematic interpretations accurately reflected their organizational context. This rigorous, transparent workflow ensured a consistent and trustworthy analysis, establishing a strong empirical foundation for the subsequent maturity assessment presented in Section 4.

3.3.2 Ensuring analytical objectivity and credibility. Given that the concept of DT is still evolving and that respondents described it from diverse disciplinary and organizational perspectives, ensuring analytical validity was a key concern throughout the study. While

Table 5. Profile of the respondents

Respondent ID	Interview duration	Years of experience	Job title	Expertise	Type of company
Section 1.0					
R1	46 min	30 years	Facility and technical property manager, district manager/area manager	Technical property management, building automation, control systems business development, operations and system/data management	Public sector Private real estate company
R2	56 min	5+ years	Head of digital transformation	Digitalization, IT architecture and change management	
R3	29 min	15+ years			
R4	58 min	21+ years	Strategic technology developer	Data analysis, AI/ML, IoT and PdM	State-owned real estate company
R5	30 min	7+ years	Strategic technology developer	Digitalization, system integration, data analytics and DT	Private real estate company
Section 2.0					
R6	47 min	3–4 years	Division manager in operations	DT, data structuring, strategy and implementation	Tech/consulting company
R7	44 min	13–14 years	Business developer	DT, smart heating, sensor systems, visualization and change management	Municipal real estate company
R8	60 min	15+ years	Head of digital transformation	DT, strategic digitalization, data integration and change management	Private real estate company
R9	26 min	7+ years	Strategic technology developer	DT, data quality, facility data infrastructure and FM strategy	Large real estate owner/manager

Source(s): Authors’ own work

subjective interpretations were inevitable, a structured and transparent analytical process minimized individual bias and increased the validity of the results. The analysis combined both theory-driven and data-driven coding, where initial codes were guided by established DT dimensions (data management, system integration, competence and strategy) but refined inductively based on emergent insights from the interviews. This hybrid approach anchored the findings in prior theoretical frameworks while allowing for empirical nuance.

To further strengthen validity, the researchers applied cross-validation procedures, including joint review of coding categories, iterative comparison of interpretations and discussion of divergent views until consensus was reached. Moreover, the identified patterns were validated through thematic saturation – no new concepts emerged after the eighth interview – and member checking, where selected respondents confirmed that the interpreted themes accurately reflected their experiences. Finally, convergence between the literature and interview findings in Sections 4 and 5 supports the analytical robustness of the conclusions. Together, these procedures ensure that while respondent views may differ, the synthesis and interpretations presented in this study reflect a valid and empirically grounded assessment of how DT implementation is understood and practiced within the studied organizations.

3.4 Maturity assessment approach

To complement the thematic analysis, a maturity assessment, as shown in Figure 2, was developed to compare how organizations have progressed in implementing DT within FM. The assessment is based on nine categories identified from both literature and interview data, such as data management, system integration, use of standards and strategic alignment.

- Red = not used; major challenges perceived;
- Yellow = partially used, notable limitations;
- Green = actively used; few or no major obstacles; and
- White = no clear assessment based on the interview.

The assessment of organizational maturity levels presented in Figure 2 was directly informed by the methodological framework described in Section 2.7 and operationalized through the empirical findings derived from the semistructured interviews. Specifically, the maturity assessment followed a qualitative coding approach aligned with the principles of digital

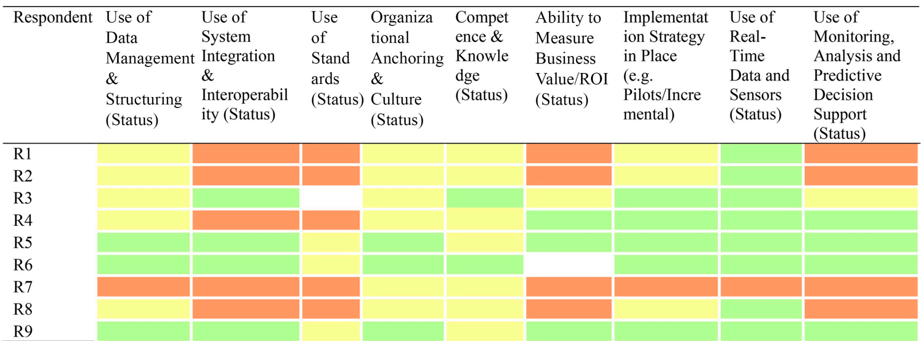


Figure 2. Maturity levels of participating organizations in key areas related to DT implementation in FM

Source: Authors' own work

transformation and sociotechnical readiness assessment (Mettler, 2011). Each dimension – data governance, system integration, organizational culture, competence and strategic alignment – was evaluated based on respondents' descriptions of current practices and perceived challenges. These qualitative indicators were then systematically compared against the predefined maturity criteria (Levels 1–5) to determine each organization's relative positioning. Thus, Figure 2 does not represent a separate or hypothetical framework, but an applied analytical synthesis grounded in empirical data interpretation. The classification captures observed patterns in the interview material, enabling a nuanced understanding of how varying digital capabilities influence DT implementation readiness within Swedish FM organizations.

To increase transparency and reproducibility, an operational rubric was developed to define explicit thresholds for each color-coded maturity category (Figure 2). Each organization's position within the rubric was determined through qualitative coding of interview data and triangulation with literature-based indicators of digital readiness. The rubric consisted of five levels, from *ad hoc* (Level 1) to optimized (Level 5), aligned with established maturity assessment frameworks (Mettler, 2011; Godager, 2024):

- *Level 1 (ad hoc – Red):* Digital practices are unstructured, with minimal or no integration of BIM or IoT systems; decision-making is reactive and data management is largely manual.
- *Level 2 (Developing – Yellow):* Initial efforts to digitize processes exist, often through isolated pilot projects or partially integrated systems, but data standards and governance remain inconsistent.
- *Level 3 (Defined – Light Green):* Digital processes are defined and repeatable across projects; structured BIM data and limited IoT integration are in place, though interoperability and analytics remain underdeveloped.
- *Level 4 (Managed – Green):* Systematic use of BIM and IoT supports proactive maintenance and decision-making; standardized data environments and collaborative workflows are in use, with increasing reliance on predictive analytics.
- *Level 5 (Optimized – Dark Green):* Full DT integration supports automated PdM, real-time analytics and continuous improvement; technical systems are interoperable and data-driven insights inform strategic decisions.

Each interview was analyzed against these criteria across nine capability dimensions (data management, system integration, standards use, organizational culture, competence, strategy, real-time data use, predictive analytics and value realization). The coded evidence was then translated into color categories to visually represent the maturity gradient.

Respondent R4 (a public facility owner) demonstrated Levels 3–4 (Defined–Managed) maturity. The organization had established BIM standards, a centralized data management system and ongoing IoT sensor integration. While interoperability challenges persisted, its maintenance operations used structured data for PdM pilot projects, aligning with "Defined–Managed" thresholds. Conversely, R7 (a small private operator) was rated Level 1 (*ad hoc*), characterized by fragmented digital processes, paper-based maintenance tracking and absence of standardization.

This operational rubric and example ensure that Figure 2 reflects empirical evaluation rather than conceptual classification, providing a transparent link between the data collection, coding process and the resulting maturity categorization.

The classification enabled structured cross-case comparison and is presented in Figure 2.

4. Results

To enhance transparency and ensure an auditable link between the empirical material and the analytical outcomes, the presentation of results integrates short *verbatim* excerpts from respondents, identified by their assigned codes (R1–R9). These quotes illustrate the underlying reasoning and experiences that informed the thematic categories and strategy elements summarized in the results section. Each major theme – such as PdM, organizational readiness, competence development, structured data and long-term vision – is supported by at least one representative quote that captures the respondent's perspective in their own words. The quotes were selected to exemplify both recurring and divergent views, thereby reinforcing the credibility and depth of interpretation. These *verbatim* excerpts are included inline throughout Section 4 to substantiate each thematic finding. By linking respondent statements directly to the analytical themes and strategy elements, the study strengthens the chain of evidence from data-coding-categories-themes-conclusions, ensuring interpretive rigor and transparency in qualitative reporting as shown in Table 6.

4.1 The main benefits and challenges of implementing digital twins for technical building maintenance within building information modeling-supported facility management processes

Table 7 summarizes the respondents' descriptions of the benefits and challenges associated with implementing DT for technical building maintenance within BIM-supported FM processes. The two columns reflect the main themes identified in the analysis: benefits, technical challenges and organizational challenges. This summary directly relates to:

RQ1. For a deeper understanding of how each respondent defines the concept of a DT, as seen in Table 8.

4.2 The key elements of a practical strategy for implementing digital twins in building maintenance

Through thematic analysis of the interview data, seven key elements were identified as critical for a practical DT implementation strategy within FM. While respondents did not describe a linear step-by-step process, recurring themes were synthesized into core components that reflect both organizational and technical conditions. Each element is grounded in empirical insights and illustrated with direct input from professionals.

4.2.1 Identifying organizational needs and challenges ("Why" *and* "What"*).* Clarifying the organization's operational needs and problems – the "why" and "what" – is essential for shaping a relevant and effective DT strategy. Respondents highlighted the importance of defining concrete use cases (R8) and linking DT efforts to measurable outcomes such as improved efficiency, cost savings and enhanced control (R1, R4, R5, R6, R7, R8 and R9). Awareness of DT's potential – especially among decision-makers – was emphasized as a key enabler for engagement and long-term commitment (R6, R7 and R8).

4.2.2 Gradient implementation – Implement incrementally and iteratively ("Start small"*).* Rather than a large-scale rollout, respondents recommend starting small via pilot projects and proof-of-concepts (POCs) (R5, R7, R8 and R9). New buildings often provide favourable conditions (e.g. existing BIM models) for initial implementation, with gradual extension to existing stock (R4, R6 and R8).

4.2.3 Structured data – A robust data foundation. A solid structure based on spatial hierarchy is essential (R6), with clear prioritization of relevant data (R5, R6, R7 and R8). Data

Table 6. Comprehensive thematic analysis showing themes, strategic elements, verbatim quotes and conclusion

Theme	Strategic element	Verbatim quote (R#)	Conclusion
Predictive maintenance	Condition-based maintenance	"You might also talk about that you can somehow change not based on service intervals but look at whether there are behaviors that start to change if an elevator vibrates abnormally…" (R3)	Predictive maintenance requires moving beyond fixed intervals to condition-based strategies
	Sensor-driven anomaly detection	"If a sensor hasn't given any value in 48 h… then we should start raising the alarm." (R4)	Algorithms and sensor data are key for early fault detection
	Operational priority	"But keeping track of your components and their condition is probably the most important thing." (R9)	Maintenance planning must prioritize component condition monitoring
	Machine learning for forecasting	"There's a machine learning model for every building." (R4)	Advanced analytics will enable proactive maintenance and resource optimization
Organizational readiness	Need for anchoring in operations	"The managers in operations need to kind of understand the point and understand the benefit of this." (R6)	Operational buy-in is critical for DT success
	Business case for management buy-in	"Who can make a good business case out of this. And show the CEO and management that this delivers." (R6)	Clear ROI communication is needed to secure leadership support
	Current siloed structure	"Now in our organization we are very much driven by specialist knowledge…" (R1)	Organizational silos hinder integrated DT strategies
	Cross-functional teams forming	"We have a team of 12 people. We are essentially very much requirements analysts, project managers, IT architects." (R3)	Teams exist but need a clearer structure and mandate
	Iterative learning and management support	"We have with management the mindset that we do some testing […] not prove everything at once." (R5)	Management must support incremental and test-driven approaches
Competence development	Need for new roles	"We needed to have someone who is a digital twin, BIM manager." (R9)	Specialized roles are essential for DT implementation
	Skills gap in traditional roles	"But these people who have worked with CAD for many years don't have those skills." (R9)	Upskilling is required to bridge traditional and digital competencies
	Early-stage skill enhancement	"In the early stages […] you need a little more of a domain architect." (R8)	Architectural and strategic skills are needed early in projects
	Internal technical expertise	"We have some guy who sits around and knocks code all the time with our data lake, a real computer nerd." (R9)	Technical skills exist but are concentrated in a few individuals

(*continued*)

Table 6. Continued

Theme	Strategic element	Verbatim quote (R#)	Conclusion
	Hiring for digital skills	"I think we definitely need to hire some people who have these skills, initially." (R5)	Organizations recognize the need for new digital competencies
Structured data	Interoperability requirement	"The Three databases need to talk to each other." (R8)	Data integration is critical for lifecycle analysis and predictive maintenance
	Importance of structured data	"As long as it's well-structured data… Then it's pretty easy to show it." (R4)	Structured data enables visualization and analytics
	Pragmatic approach to data quality	"We say that it is better to map a little that you verify and know is correct than to map everything." (R9)	Focus on verified core data before scaling DT
	Need for aggregation and efficient architecture	"There will be a lot of data, which means we have to build cubes of it to be able to consume it quickly." (R4)	Scalable data architecture is necessary for real-time insights
	Data maturity challenge	"It's unstructured data. Which you can get help with using AI to structure." (R2)	AI can assist in structuring legacy data, but foundational work is needed
Long-term vision	Future-oriented planning	"Start small, I would say. And don't beat the drum." (R7)	Gradual scaling and pilot projects are preferred over "big bang" approaches
	Vision of AI integration	"You'll have a little AI agent that you tell things to." (R9)	AI-driven decision support is seen as a future enabler for DT
	Expectation of structured benefits	"Now we want this and we have seen these benefits. And figure out a business case for this." (R7)	Clear economic justification is essential for scaling DT
	Scalability needs	"How do you keep track of this maintenance? You can't have 1.2 million square meters in Excel files." (R7)	Large-scale DT adoption requires robust digital infrastructure
	Visionary perspective	"And somewhere up there at the top there's like being able to use AI. And deep learning to perform smart analyses in different ways." (R2)	Long-term vision includes AI and advanced analytics for efficiency

Source(s): Authors' own work

Table 7. Summary of benefits, challenges and practical strategy for implementation of DT in building maintenance

Benefits	Challenges
Process efficiency and workflow improvement (R6, R1 and R5)	*Technical challenges*
Predictive maintenance (R1, R3, R4 and R5)	System integration and data interoperability (R1, R3, R4 and R7)
Data-driven decision support and new insights (R3, R4, R5, R6 and R8)	Data management, quality and accessibility (R3, R4, R6 and R8)
Improved overview and control (R5, R6 and R9)	Standardization and interoperability (R1, R7 and R8)
Resource optimization and more efficient use (R4, R5, R6 and R7)	*Organizational challenges*
Cost savings (R4, R5 and R9)	Organizational culture and resistance to change (R1, R3, R4, R7 and R9)
Improved documentation and information accessibility (R1, R6 and R7)	Competence and knowledge gaps (R5 and R7)
Support for sustainability reporting (R9)	Economics and business value (R1, R3 and R5)
	Policy and legal aspects (R4 and R6)

Source(s): Authors' own work

quality and integration – from static, event-based and real-time sources – are key for functionality (R3, R4, R8 and R9). Master data management is used to maintain consistency (R9).

4.2.4 Systems – Select and integrate the right systems and technologies. System integration is central (R4–R9), favoring a "best-of-breed" approach for modular functionality (R5, R8 and R9). Application programming interfaces (APIs) facilitate interoperability (R5, R6 and R9). Core technologies include BIM, IoT sensors, control systems, FM platforms and analytics tools, with data visualization supporting usability and collaboration (R1, R4, R5, R6, R7, R8 and R9).

4.2.5 Organization capacity and workforce competence – Focus on the organization and its people. DT implementation requires internal anchoring and cultural readiness (R6), involving staff at all levels (R5 and R8). Upskilling is essential (R7 and R9), potentially requiring new roles like data architects and DT/BIM specialists (R6, R7, R8 and R9). Strategies must match the organization's digital maturity (R5, R8 and R9).

4.2.6 Standards and collaboration – Enabling interoperability. To align data across project phases and systems, early definition of delivery requirements is crucial (R4, R5 and R9). Adherence to standards like Bricks and RealEstateCore, as well as internal guidelines such as BIM manuals, is recommended (R4 and R9). Improved cross-disciplinary communication is also emphasized (R5 and R7).

4.2.7 Vision and patience – Maintain a long-term vision. DT adoption is seen as a long-term transformation (R6 and R8). Strategies should be future-oriented, gradually realizing benefits such as AI-driven PdM and automation (R2, R4, R5, R8 and R9), transitioning from passive digital replicas to active, intelligent DT (R8).

5. Discussion

5.1 The main benefits and challenges of implementing digital twins for technical building maintenance within building information modeling-supported facility management processes

This *RQ* was addressed through both the literature review (Sections 2.2, 2.3 and 2.4) and interviews with industry professionals (Section 4.1). A strong alignment was observed

Table 8. Summarizes respondents' definitions of DT

Respondent	Section	Definition of DT
R1	1.0	Views DT as a tool to improve workflow, enhance visualization and collaboration, support maintenance planning and enable PdM, while noting challenges with formats and standards
R2	1.0	Sees DT as a way to integrate and visualize data from multiple systems to optimize operations, reduce error reports and enhance customer interaction – highlighting the need for quality-assured data, proper infrastructure and seamless information flow from project to operation
R3	1.0	Believes a true DT must include data and sensors. They highlight its potential to improve maintenance planning, centralize scattered data, enhance stakeholder understanding, support onboarding and scale property management, while emphasizing the need for better data quality, BIM handling and change management
R4	1.0	Describes DT primarily as visualization tools without built-in intelligence, used to display sensor and control system data. They note the potential for integrating BIM and showing component relationships, but emphasize challenges in defining value and fully utilizing data-driven capabilities
R5	1.0	Defines the DT mainly as a tool for tracking spatial placement and surfaces, emphasizing its current role in visualization. While they envision future integration of AI and sensor data, their present use focuses on managing spatial information
R6	2.0	Views the DT as a methodology, a way of working to create a digital counterpart of a physical asset by integrating data from different system silos to enable improved analysis and management. Visualization is part of it, but not the core definition
R7	2.0	Finds it difficult to define a DT, especially distinguishing it from advanced BIM or three-dimensional models. However, they believe that real DT must include data and sensors to qualify
R8	2.0	Offers a conceptual view of DT, defining them as the integration of three data types: issue reports, object data and product data, necessary for lifecycle analysis and PdM. They emphasize that maintaining and updating these data sets forms the core of a DT
R9	2.0	Sees the DT as a centralized digital representation of a building that collects and structures data from sources like BIM and sensors. It is used to visualize spatial information, display real-time data and support troubleshooting by linking issues to physical locations and systems

Source(s): Authors' own work

between theoretical insights and practical experiences regarding the benefits and challenges of applying DT to technical building maintenance within BIM-supported FM contexts.

5.1.1 Benefits of digital twins for building maintenance. Both the literature and the interview findings highlight several key benefits of DT for FM and maintenance.

5.1.1.1 Predictive maintenance as a key benefit. One of the most frequently emphasized advantages is PdM. Literature highlights how DT, when integrated with sensors (IoT) and real-time data, enables continuous monitoring and data-driven decisions that help prevent failures (Li *et al.*, 2023; Desogus *et al.*, 2021; El-Din *et al.*, 2022; Shuhaimi *et al.*, 2024). This enables a shift toward predictive "predict-and-prevent" strategies (Gispert *et al.*, 2025). Several respondents (R1, R3, R4 and R5) confirmed PdM as a central benefit, particularly in relation to improved operational control, extended asset lifespan and reduced need for emergency interventions.

5.1.1.2 Improved efficiency and decision-making. DT are described in the literature as tools that enhance maintenance processes through better decision-making, operational efficiency and predictive capabilities (Desogus *et al.*, 2021; Shuhaimi *et al.*, 2024; El-Din *et al.*, 2022; Madubuike *et al.*, 2022). DT provides continuous insights and real-time data to support data-driven decisions. Respondents confirmed similar benefits, referring to process efficiency (R6, R1 and R5), data-driven decision support (R3, R4, R5, R6 and R8) and improved control (R5, R6 and R9), reinforcing the literature's view on DT's potential to improve FM outcomes.

5.1.1.3 Cost savings and resource optimization. The literature highlights DT's potential to reduce operational costs and improve energy efficiency through PdM and intelligent system control (Madubuike *et al.*, 2022; Cespedes-Cubides and Jradi, 2024; Yoon, 2024; Li *et al.*, 2023; AlBalkhy *et al.*, 2024). Li *et al.* (2023) report energy savings of up to 30%. Respondents (R4, R5 and R9) mentioned cost savings, while others (R4, R5, R6 and R7) emphasized resource optimization, reinforcing the link between PdM, efficiency and reduced operational waste.

5.1.1.4 Improved access to information and documentation. DT can offer a unified digital representation by integrating data from various sources, such as BIM models and sensors (Madubuike *et al.*, 2022; El-Din *et al.*, 2022). Respondents (R1, R6 and R7) identified improved documentation and information accessibility as a clear benefit. The literature also stresses the importance of structured data management, often enabled through CDE to ensure effective information sharing (ISO, 2019; Godager, 2024; El-Din *et al.*, 2022).

5.1.2 Challenges of implementing digital twins. The implementation of DT faces significant challenges, as confirmed by both the literature and interview findings.

5.1.2.1 Data integration and interoperability. The literature highlights challenges with integrating data from BIM and IoT systems, including vendor incompatibility and updating asset data (Gispert *et al.*, 2025; Cespedes-Cubides and Jradi, 2024; Shuhaimi *et al.*, 2024). Interviewees (R1, R3, R4 and R7) confirmed system integration and data interoperability as a major technical challenge.

5.1.2.2 Lack of standardization. The lack of shared standards complicates data quality and DT adoption (Cespedes-Cubides and Jradi, 2024; AlBalkhy *et al.*, 2024; El-Din *et al.*, 2022; Godager, 2024; Madubuike *et al.*, 2022). Although ISO 19650 offers a foundation, it lacks practical guidance for DT integration (El-Din *et al.*, 2022). Respondents (R1, R7 and R8) similarly noted standardization and interoperability as key technical challenges.

5.1.2.3 Organizational challenges. Literature and interviews highlight organizational resistance, lack of readiness and low stakeholder engagement as key barriers to DT adoption (AlBalkhy *et al.*, 2024; Hauashdh *et al.*, 2024; Hunhevicz *et al.*, 2022). Challenges include fragmented industry structures, unclear roles, poor documentation and cost-driven cultures that hinder long-term thinking (Hauashdh *et al.*, 2024). Respondents (R1, R3, R4, R7 and R9) likewise emphasized resistance to change and cultural barriers as major obstacles.

5.1.2.4 Competence and knowledge gaps. A lack of understanding and practical knowledge of the DT concept among professionals is identified in the literature as a key challenge (AlBalkhy *et al.*, 2024). This is echoed in the interviews, where respondents (R5 and R7) highlighted competence and knowledge gaps as organizational barriers to successful implementation.

5.1.2.5 Costs and business value. The high cost of implementing technologies such as IoT sensors is highlighted in the literature as a barrier to DT adoption (Shuhaimi *et al.*, 2024). Respondents (R1, R3 and R5) pointed to economics and business value as a challenge, particularly in demonstrating return on investment (ROI) and justifying DT-related expenditures.

5.1.2.6 Data management and quality. The literature identifies defining, managing and ensuring access to necessary data as a key technological challenge (AlBalkhy *et al.*, 2024). Respondents (R3, R4, R6 and R8) referred to data management, quality and accessibility as critical, emphasizing that poor data quality can hinder effective DT implementation.

5.1.2.7 Lack of practical implementation guidance. A major challenge highlighted in the literature is the absence of comprehensive and practical guidance or manuals for implementing DT in the construction sector (Hauashdh *et al.*, 2024; De Rubeis *et al.*, 2023; Madubuike *et al.*, 2022). Although some frameworks and processes have been proposed, there is still no widely accepted, actionable strategy (De Rubeis *et al.*, 2023; El-Din *et al.*, 2022). This gap also forms the basis for the aim of this study.

The results show that implementation of DT faces several intertwined technical, organizational and economic disadvantages. Table 9 summarizes the potential disadvantages of implementing DT in PdM.

5.1.3 Variation in definitions and implications. As shown in Table 8, respondents held varying interpretations of DT. While the thematic patterns were consistent, this conceptual variation may affect how organizations perceive benefits and challenges, underscoring the need for a shared internal definition.

5.2 The key elements of a practical strategy for implementing digital twins in building maintenance

The development of the seven key elements, and their subsequent structuring into the multilevel model (Figure 3), is not conceived in isolation but is fundamentally grounded in the organizational and technical preconditions identified in the theoretical framework (Section 2.7). The work of Godager (2024) and El-Din *et al.* (2022) establishes core prerequisites for DT success, such as the definition of information requirements (OIR/AIR), the need for lifecycle-based information strategies, stakeholder engagement and a robust technical foundation comprising BIM, IoT and CDEs. The proposed model synthesizes and structures these foundational concepts into an actionable, layered strategy, moving from theoretical prerequisites to a phased implementation pathway.

Based on the combined findings from the literature (Section 2.7) and thematic interview analysis (Section 4.2), seven key elements were identified as central to a practical DT implementation strategy in FM. Some elements are prerequisites for others, requiring a more layered understanding. To reflect these interdependencies, a triangular model is proposed as shown in Figure 3, where the elements are structured into three levels: foundational conditions (base), implementation (middle) and long-term direction (top). The model

Table 9. Potential disadvantages of implementing digital twins for predictive maintenance

Challenge	Description	Impact on predictive maintenance (PdM)
Data integration and interoperability issues	Difficulty in combining data from BIM, IoT and FM systems due to vendor incompatibility and fragmented data environments	Leads to incomplete or inconsistent data sets, reducing the accuracy and reliability of PdM insights
Lack of standardization	Absence of shared frameworks and practical standards (e.g. beyond ISO 19650) for DT implementation	Causes inconsistency in data formats and exchange, limiting scalability and interoperability of PdM solutions
High implementation and operational costs	High initial investments in sensors, analytics tools and data infrastructure, with uncertain ROI	Limits adoption, especially among cost-sensitive organizations, and discourages long-term PdM integration
Organizational and cultural resistance	Resistance to change, unclear roles and siloed workflows in FM organizations	Slows DT adoption and weakens cross-disciplinary collaboration required for PdM
Competence and knowledge gaps	Lack of skilled personnel in BIM, IoT and data analytics for managing DT systems	Reduces the ability to design, maintain and interpret predictive models effectively
Data management and quality concerns	Inconsistent, incomplete or poor-quality data from sensors and models	Produces unreliable predictions, false alarms or missed maintenance needs
Lack of practical implementation guidance	Few comprehensive, actionable frameworks for DT deployment in real-world FM contexts	Causes uncertainty and inconsistency in PdM project planning and execution
Variation in DT definitions and understanding	Different interpretations of the DT concept across organizations	Creates confusion in project goals, KPIs and expected PdM outcomes
Dependence on organizational maturity	Success relies on the organization's existing digital maturity and data infrastructure	Low-maturity organizations struggle to reach the predictive stage of DT utilization
Long-Term Vision and Patience Required	DT and PdM implementation require incremental development and ongoing commitment	Early lack of results may discourage stakeholders, jeopardizing the sustainability of DT initiatives

Source(s): Authors' own work

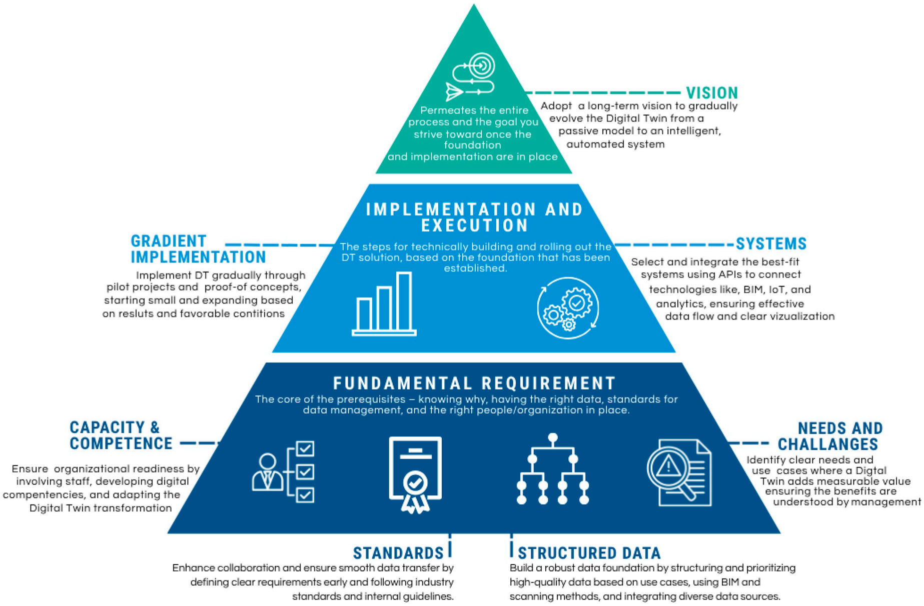


Figure 3. Layered strategy model for DT implementation, based on identified key elements
Source: Authors' own work

emphasizes that success depends on establishing the right foundations before scaling systems or aiming for advanced outcomes.

5.2.1 Base layer: Foundational conditions. The base of the triangle includes elements that must be in place before DT implementation can begin effectively.

5.2.1.1 Identify needs and challenges – The "Why" and "What". A clear purpose and defined value are essential. Literature and respondents emphasize the importance of identifying organizational needs, defining use cases and linking them to measurable outcomes, supported by frameworks such as OIR and AIR (Godager, 2024; El-Din *et al.*, 2022). Structured data and standards are considered hygiene factors – without them, DT adoption cannot scale. Structured data – A robust data foundation DT depends on integrating real-world data with structured BIM information, supported by standardized CDEs (Godager, 2024; El-Din *et al.*, 2022). Respondents emphasized the need for solid data structures, high quality and the integration of different data types. These insights align with literature highlighting data complexity and the need for standardization (Cespedes-Cubides and Jradi, 2024).

5.2.1.2 Standards and collaboration – Enabling interoperability. Both literature and interviews stress the need for standardized frameworks to overcome fragmentation and enable cross-disciplinary collaboration (El-Din *et al.*, 2022; Madubuike *et al.*, 2022). ISO 19650 is a key reference (ISO, 2019). Respondents recommended defining delivery requirements early, aligning with FM systems, adopting standards like BRICK and RealEstateCore and developing internal BIM manuals.

5.2.1.3 Organization capacity and competence. Focus on the organization and its people implementing DT requires addressing both human and technical challenges (Godager, 2024;

El-Din *et al.*, 2022). Success depends on alignment with business and information strategies, clear roles, digital skills and cultural readiness (Godager, 2024). Respondents viewed DT as an organizational transformation, emphasizing the need for internal anchoring, staff involvement, competence development and potentially new roles (e.g. data architects and BIM/DT specialists). Adapting processes and interfaces to users' digital maturity was also seen as essential.

5.2.2 Middle layer: Implementation and execution. Once foundational conditions are in place, organizations can focus on the technical rollout and how implementation is approached in practice:

5.2.2.1 Systems – Select and integrate the right systems and technologies. The literature identifies BIM, IoT/sensors, data management tools and AI/ML as key components of DT systems (Godager, 2024). Respondents supported a "best-of-breed" approach, integrating purpose-specific systems via APIs. They highlighted the use of BIM, sensors, control and maintenance systems, data analytics and visualization tools, reinforcing the literature's technical emphasis with practical insights into integration strategies.

5.2.2.2 Gradient implementation – Implement incrementally and iteratively ("Start Small"). Respondents emphasized the importance of starting small, with POC or pilot projects and scaling gradually based on lessons learned and demonstrated value. New construction projects were seen as favorable starting points. While the literature does not explicitly frame this as "start small," it aligns with the need for user- and value-driven strategies that guide technical decisions toward long-term outcomes (Godager, 2024; El-Din *et al.*, 2022). Jacobsson and Linderoth (2010) also advocate for a gradual implementation of complex technologies when feasible, such as BIM. BIM applications can be introduced gradually, for instance, starting with clash detection, where users are likely to perceive benefits early in the process, as this strengthens motivation and supports the adoption of the technology. However, early success may not be enough to secure long-term investment. High initial costs and uncertainty about value can hinder even first steps, highlighting the need for a long-term vision and management support.

5.2.3 Top layer: Vision and long-term direction. The top of the triangle represents the overarching mindset and long-term orientation needed to guide and sustain DT implementation:

5.2.3.1 Vision and patience – Maintain a long-term vision. Respondents described DT implementation as a long-term journey requiring a forward-looking strategy. The goal is to gradually evolve from a passive digital replica to an active, intelligent DT capable of AI-driven PdM and automation. This aligns with the literature, which emphasizes strategic alignment as essential for delivering long-term value (Godager, 2024).

To ground the proposed model in a specific management context, it can be illustratively applied to the profile of Respondent 4 (R4), a public facility owner with a medium-high maturity level. R4's organizational context demonstrates the model's practical relevance. Their established strengths were primarily in the base layer: a clear understanding of operational needs ("Why/What"), a robust foundation of structured data and active engagement with standards for interoperability. This strong base enabled them to initiate middle-layer activities, such as piloting system integrations. However, R4 concurrently faced challenges emblematic of this implementation layer, including technical hurdles in selecting and integrating the right "best-of-breed" systems and organizational gaps in workforce competence for managing the new digital tools. This alignment shows that the model accurately reflects their real-world situation: a solid foundation allowed for implementation efforts, which, in turn, revealed the next set of challenges to be addressed. For R4, the strategic imperative, as guided by the model, is to focus on resolving these mid-layer integration and competence issues to progress toward the top-layer vision of a fully active, intelligent DT. This example confirms the model's utility in diagnosing an organization's position and prioritizing strategic actions based on its specific maturity profile.

5.2.4 The strategy in relation to challenges and organizational maturity. The triangle model illustrates that DT implementation is not a linear process. More advanced actions depend on foundational conditions, such as need identification, structured data, standards and competence, which are often lacking in less mature organizations. As discussed in Section 5.1, many challenges reflect weaknesses in these foundational areas. Therefore, the strategy must be adapted to the organization's current maturity level. Figure 3 presents this as a layered model rather than a sequential process. The discussion is based on empirical insights from interviews (Section 4.2) and supported by the literature (Section 2.7), reinforcing its practical relevance. Based on this layered interpretation, the following section summarizes how the findings address the two *RQs*.

5.3 Summary of findings for Research Questions 1 and 2

This study explored the role of DT in building maintenance through two *RQs*. For *RQ1*, literature and interviews aligned on key benefits, such as PdM, efficiency and decision-making, and on recurring challenges like data integration, lack of standards, organizational resistance, competence gaps and implementation costs. While the literature offered theoretical grounding, interviews provided operational depth and showed how challenges appear in practice. *RQ2* focused on identifying practical strategy elements. Here too, literature and industry perspectives converged, highlighting the importance of value-driven use cases, incremental implementation, structured data, system integration, organizational anchoring and long-term vision. Interview data translated these principles into actionable steps directly linked to *RQ1* challenges. Together, the findings form the basis for the layered strategy model presented in Figure 3. While the strategy provides structure, each step represents a complex topic that may warrant further study. Areas like data integration, culture and competence require contextual adaptation and long-term commitment.

5.4 Methodological reflections

This study was conducted using a qualitative and explorative approach, suitable for addressing complex and relatively new areas such as DT implementation in FM. The process was iterative and informed by both theoretical literature and empirical insights from semistructured interviews. As the study progressed, recurring patterns and themes were identified, which guided the formulation of a structured implementation strategy. The combination of literature review and interview analysis enabled the researchers to move between theory and practice, refining the strategy based on emerging insights. This process allowed for continuous development and ensured that the resulting implementation strategy, structured as a layered model, was both theoretically informed and grounded in real-world experience.

5.4.1 Validity and reliability. To ensure the trustworthiness of the findings, both validity and reliability were actively addressed throughout the research process. Validity refers to the extent to which the study investigates what it is intended to examine, in this case, the maturity of DT implementation within FM. By focusing the analysis on organizations with higher maturity levels, conclusions could be based on responses from participants with demonstrated experience and relevant insight. The respondents were selected through purposive sampling based on relevant expertise in building maintenance and digitalization. The sample included both public and private actors with varying levels of digital maturity, which increased the relevance of the insights and strengthened the study's validity. The validity of the developed strategy is supported by its foundation in both literature and recurring patterns in the interview data. However, its applicability may vary depending on organizational context, and future testing in practice is recommended to further strengthen its validity. Reliability, in turn, concerns the consistency and repeatability of the results. To strengthen this aspect, a systematic approach was used to categorize maturity levels, thereby reducing subjective interpretation and increasing the likelihood that similar outcomes could be achieved by other researchers applying the same framework.

5.4.2 Assessment of organizational maturity levels. The maturity assessment presented in Figure 2 (see Section 3.3) provides a comparative overview of how the interviewed organizations have progressed in their implementation and use of DT technologies within FM. The analysis highlights clear differences in adoption across categories such as data management, system integration and strategic alignment. These variations help explain several of the challenges discussed in Section 5.1 and provide further context to the need for adaptable implementation strategies (see Section 5.2).

The assessment of organizational maturity in DT implementation evaluates how well an organization's structures, technologies and practices enable effective and sustained DT adoption within FM. It is a multidimensional framework that identifies progress along both technical and organizational dimensions. Each dimension corresponds to a capability domain that influences readiness and performance in DT-driven operations.

5.4.2.1 Conceptual foundation. The assessment of organizational maturity for DT implementation in FM is grounded in capability maturity models and sociotechnical systems theory. It evaluates how effectively an organization integrates digital, technical and human capabilities to support data-driven decision-making throughout a building's lifecycle. Maturity reflects the organization's progression from fragmented, project-based digital practices toward systematic, standardized and optimized DT-enabled operations.

5.4.2.2 Assessment dimensions and indicators. Maturity is measured across several interdependent dimensions, including data management, system integration, standards adoption, organizational culture, competence, business value assessment, implementation strategy, use of real-time data and predictive decision support. Each dimension captures a key capability influencing digital readiness – from managing structured data and ensuring interoperability to developing staff expertise and leveraging AI for PdM.

5.4.2.3 Methodology for assessment. The assessment employs a mixed qualitative approach, typically combining semistructured interviews with key stakeholders, document analysis and cross-case comparison. Organizations are evaluated along maturity scales – ranging from low (*ad hoc*) to high (optimized) – for each dimension. The resulting data are summarized in Figure 2, enabling a holistic comparison of technical and organizational competencies across cases.

5.4.2.4 Analytical interpretation. The maturity analysis provides diagnostic and strategic insights. Diagnostically, it identifies each organization's position on the digital transformation curve, revealing strengths such as strong data governance or weaknesses such as low cultural readiness. Strategically, it guides improvement efforts, showing whether the focus should be on enhancing technical infrastructure, developing workforce competence or aligning digital initiatives with business objectives.

5.4.2.5 Practical application. Assessing organizational maturity offers a framework for benchmarking FM organizations, prioritizing investment and shaping DT implementation roadmaps. It supports continuous improvement by linking maturity growth to measurable outcomes such as cost reduction, operational efficiency and PdM capability. Over time, it enables monitoring of digital transformation progress and provides a structured pathway toward fully integrated, intelligent and sustainable FM practices.

5.4.3 Reflections on the categorization process. During the assessment, the need to adjust some initial placements was identified. R7 and R8 were first categorized under Section 2, despite showing low maturity across most indicators, while R3, R4 and R5 demonstrated higher integration, standard use and advanced practices like real-time monitoring and predictive support, better fitting Section 2. This highlights the importance of validating categorizations and how the maturity model reveals inconsistencies in coding. Table 5 also helped differentiate insights from more and less mature respondents, allowing nuanced interpretation. Strategic conclusions, such as those on implementation or predictive support, were mainly drawn from organizations with predominantly green profiles.

5.5 Further research

Further research could beneficially focus on three key areas: (1) validating and further developing the maturity assessment framework used in this study (Table 5), to enable broader mapping of DT maturity across the FM sector and to identify factors that influence progress in areas such as data integration, organizational anchoring and standardization; (2) analyzing the variations observed between respondents and their organizations (Table 4 and Figure 2) to understand which strategies, resources and contextual factors contribute to successful implementation of DT solutions; and (3) testing and validating the proposed layered strategy model in real-world settings, for example, through case studies or pilot projects, as the strategy offers a concrete response to the lack of practical guidance previously identified in the literature.

6. Conclusions

This study addresses a key gap in the literature: the lack of practical guidance for implementing DT in the FM sector. By combining theoretical insights with empirical findings from industry professionals, the study proposes a structured strategy consisting of seven key elements to support DT adoption in FM. The strategy is grounded in real-world conditions and based on recurring themes from thematic analysis. The elements cover both technical and organizational aspects, ranging from need identification, structured data and system integration to competence, internal anchoring and long-term vision. Presented as a layered triangle, the model highlights that foundational conditions must be established before implementation can scale effectively. The findings show that successful DT implementation requires alignment between technology, processes and people. Lifecycle-based information strategies (e.g. OIR, AIR and LOIN), together with digital infrastructure (BIM, IoT and CDE), are essential for achieving efficiency, interoperability and long-term value. The maturity assessment (Table 5, Section 3.3) further illustrates how organizational readiness in areas like data quality and digital competence affects strategy applicability. More mature organizations offered the most actionable insights, reinforcing the need to adapt the strategy to varying levels of maturity. In conclusion, the proposed model serves as a starting point to adopt DT-driven PdM. Future research should test and refine it in practice, exploring its adaptability across different organizational types, use cases and maturity levels.

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