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Review Article

Leveraging Building Information Modelling to Advance Sustainable Building Maintenance

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Abstract

Globally, ageing buildings require regular upkeep to maintain performance and user comfort. However, building maintenance is challenging, as it often prioritises short-term functionality over environmental performance and lifecycle efficiency, which highlights the need for a more sustainable approach. This creates a need for 'sustainable maintenance' that involves planning and conducting building maintenance activities in ways that reduce resource use, minimise waste and emissions, improve occupant comfort, and control costs. Digital tools such as Building Information Modelling (BIM) can support these goals by enabling accurate information management, predictive planning, and performance tracking throughout a building's lifecycle. However, BIM's potential, including better design coordination, reduced material waste, and informed decision-making, is realised mainly in design phases, with limited application in operation and maintenance, especially for sustainable practices. This research aims to address this gap, which concerns the lack of systematic understanding and application of BIM to advance sustainable maintenance practices in buildings, by conducting a systematic literature review (SLR) to summarise the most recent advancements and gather evidence-based insights on barriers, enablers, and best practices. The SLR forms the basis of proposing a conceptual BIM for sustainable maintenance (BIM4SM) framework, tailored to public institutional buildings, that uniquely integrates sustainability indicators into BIM-enabled maintenance workflows. Overall, results demonstrate the potential of a structured method for integrating sustainability considerations into maintenance planning and execution that would enable more efficient use of resources, extend the service life of assets, reduce environmental impacts, and promote improved decision-making by facility managers, policymakers, and other stakeholders.

Keywords: Public Buildings, Sustainability, Built Environment, Digital Tools, Building lifecycle.

Highlights

- Increasing role of building maintenance in climate adaptation and mitigation efforts can be facilitated by advanced digital tools.
- Adoption of digital tools (e.g., BIM) remains limited in the operations and maintenance phase of buildings.
- A BIM for sustainable maintenance (BIM4SM) framework has been developed to ensure effective maintenance planning and execution with minimal environmental impacts.

1 Introduction

The global construction industry greatly impacts the environment, economy, and social development. Infrastructure maintenance presents an added challenge to the Architecture, Engineering, and Construction (AEC) industry, as constant upkeep is demanded to retain the performance of the building. However, most maintenance practices only focus on simple repair, which keeps the building functional but does not really focus on efficiency and sustainability (Ighravwe and Oke, 2019). Hence, 'sustainable maintenance' is a concept that needs greater efforts and adoption across the building lifecycle (Chan, 2014; Hauashdh *et al.*, 2022a). Sustainable maintenance is framed as a strategic shift from reactive to preventive and predictive maintenance, embedding sustainability principles into building operations (Hauashdh.et al., 2022b).

However, it is challenging to plan for sustainable maintenance upfront. This is where digital advancements in the construction industry create a shift in the way traditional maintenance generally performs its work. Digital tools that include Building Information Modelling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning (ML) exhibit the potential to optimise the way operators plan, deliver, manage, operate, and maintain building assets in today's world. (Pomè *et al.*, 2023). According to a strategic report by Autodesk, use of BIM in the design stage in some developing markets is reported to be around 20% (India), and Operation & Maintenance(O&M) -stage adoption is described qualitatively as "low" (BIM's Strategic Return on Investment (ROI) Report, 2020). Matarneh et al. (2019) Also concluded that the focus of the studies on BIM was on providing real-time data access, rather than a process for seamless information exchange to overcome the interoperability issues between BIM and Facility Management (FM) systems.

This kind of gap prevents facilities from leveraging BIM's potential for predictive maintenance and lifecycle optimisation. The academic efforts focused on sustainable maintenance in general and digital workflow adoption in particular remain nascent. Therefore, this paper systematically reviews various studies to gather evidence and factors that directly or indirectly affect the optimisation of building sustainable maintenance. The basis of the research helps in the identification of various sustainable KPIs that would facilitate information sharing and improve not only data interpretation but also the development of a standardised procedure for all relevant stakeholders. The study further proposes a conceptual framework to guide future practices in sustainable maintenance across the entire building system. The outcomes of this study are intended to benefit facility managers, building owners, policymakers, and AEC professionals by providing structured knowledge, measurable indicators, and guiding principles for advancing sustainable building maintenance.

2 Research Background

The built environment is certainly one of the dominant stakeholders of sustainable development (Yiu, 2007). The built environment has been the subject of countless studies, but most of them concentrate on how they designed and affects the environment, such as determining pollution levels or accounting for greenhouse gas emissions or changing into a better ecosystem. The following section discusses the concept of sustainable maintenance from the literature.

2.1 Sustainable Maintenance (SM)

It is clear from the definitions of sustainable development and sustainable design found in literature that sustainable building maintenance would imply a practice in which building operations and maintenance are planned and executed in a resource-efficient manner, causing minimal or no impact on the environment, the building, and/or its occupants, and guaranteeing the facility's continued comfort, usefulness, and aesthetic appeal over the course of its life cycle (Lysias Frank, 2011). SM is the integration of environmental responsibility, economic efficiency, and social well-being into maintenance strategies, enabling public institutional buildings to achieve long-term value and resilience (Hauashdh et al., 2022b). Even though a broader concept of sustainable maintenance exists in literature, the nuances around its implementation, performance benchmarks, and success criteria for the global diversity of built environments remain poorly defined.

Studies show that there is a significant lack of systematic focus on O&M, thereby preventing the realisation of lifecycle sustainability benefits (Matos *et al.*, 2021). This necessitates the need to embed sustainability indicators, predictive maintenance, and data-driven decision-making into the long-term management of public buildings. Additionally, research trends and patterns reveal that there is a continuously growing interest in facilities information management using BIM, which is a potential platform for SM integration and is discussed further.

2.2 Building Information Modelling (BIM) technology

In recent years, BIM has emerged as one of the most promising technologies in the sector because of the advantages it offers, which act as an important tool in terms of precise 3D modelling, integrated collaboration, and reliable information flow from start to finish (Lysias Frank, 2011). Findings confirm that BIM is a crucial technology for achieving financial efficiency, sustainability, and productivity in construction, and that it should be considered an industry standard for future-ready infrastructure development (Sharma *et al.*, 2025).

However, a seamless information exchange process between BIM and FM systems does not yet exist (Matarneh *et al.*, 2019). Interoperability issues, along with a reliance on theoretical or survey-based models, further constrain the practical application of BIM during the O&M phase. Much of the existing research has focused only on the earlier stages of a project. For example, Olatunji (2010) examined BIM-based quantity measurement limited to the design and construction phases, while (Mitchell, 2013) Applied 5D BIM in these phases to ensure cost certainty and improved building delivery. Consequently, the O&M stage remains the weakest link, where the potential of BIM to drive sustainability is still underutilized. Only a limited number of studies have investigated BIM for energy management. Among them, Matarneh et al. (2019) demonstrated how BIM can be used to monitor, analyse, and optimize facility system performance,for more efficient building management. The following section explores how SM can be enabled through BIM.

2.3 Digital BIM integration into Advanced Sustainable Maintenance

BIM's effectiveness in sustainable building maintenance is greatly enhanced through its integration with specialized tools, technologies, and data standards. The foundation of BIM technology, used for 5D cost estimating, begins with the production of a 3D model using Revit, followed by 4D scheduling and clash detection using Navisworks and CostX (Sharma *et al.*, 2025). The main BIM-based information consists of a COBie data sheet and an IFC-based BIM model, which together represent detailed geometric and non-geometric information (Kimet al., 2018), thereby bridging the gap between design and facility management.

Through 6D BIM, environmental performance data such as energy consumption, carbon emissions, and HVAC system efficiency can be integrated into the model (Sharma *et al.*, 2025). Similarly, the application of digital twin and BIM technologies in the maintenance of industrial college building complexes has been shown to improve maintenance efficiency, promote sustainability, and create opportunities for training future talent (Zhang, 2023). Together, these integration components transform BIM from a design-stage tool into a comprehensive lifecycle management system, aligning maintenance decisions with sustainability, efficiency, and resilience objectives.

Despite these advances, several barriers remain. Lack of tools (26%) and complicated models (22%) hinder the practitioners from adopting green BIM technology. Technical compatibility issues, such as the interoperability of the BIM tool with other sustainability analysis models, for example, supporting the gbXML format (Green Building XML schema), an open schema developed to facilitate the transfer of building data stored in BIM to energy analysis tools, are significant issues (Wong andZhou, 2015). Furthermore, Matarneh et al. (2019) highlight the need for standardised feedback loops between operations and design phases, enabling real-world operational data to inform more efficient facility design.

There is, therefore, a need for a framework that will embed sustainability performance indicators into BIM-enabled maintenance workflows, transforming traditional practices into proactive, future-ready strategies. (Hauashdh et al., 2024). This underscores a BIM4SM framework, specifically designed to close information gaps between design and maintenance and facilitate effective, sustainability-focused decision-making across the building lifecycle.

3 Methodology

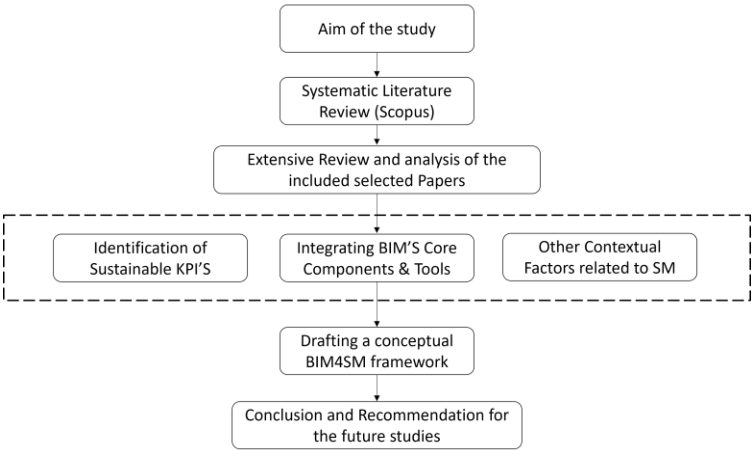

Figure 1 Research Methodology

To understand the current state of sustainable maintenance research and practice, this study analysed the advancements made in this area during the last two decades. Figure 1 provides a detailed methodological approach adopted for this study. The first phase is to perform a detailed systematic literature review (SLR) of how a BIM-integrated framework could be used for sustainable maintenance. The research employed a PRISMA methodology (see Fig. 2) to identify and select articles relevant to the study. (Moher et al., 2009). The detailed methodology is shown in Figure 2. For this, a comprehensive literature search based on the 'title/abstract/keyword' search method was first conducted through the scholarly publication search engine (Scopus).

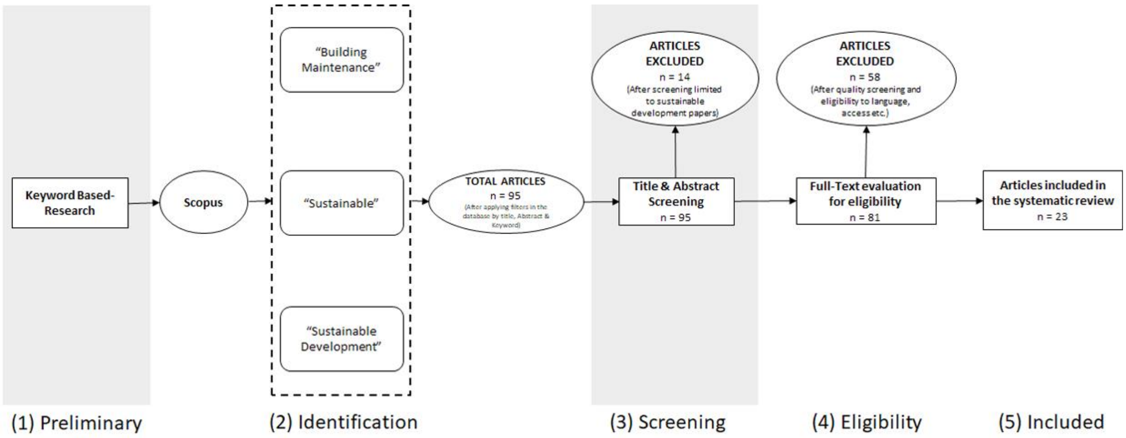

Figure 2 Flowchart of the PRISMA methodology for literature selection

The keywords used in the literature search included 'Building Maintenance,' 'Sustainable Development,' and 'Sustainable.' Conferences and articles, Journals, technical papers, and review papers covering the stages of the building lifecycle that have these keywords in their titles, abstracts, or keywords are being considered for publication in reputable journals or conference proceedings. Since sustainable building maintenance is a new technological advancement, articles published between 2005 and 2025 are considered. Article types such as book reviews, editorials, letters to the editor, talks, closures, and comments were not included. Eighty-one papers were filtered during this process, and twenty-three BIM-integrated sustainable maintenance-related papers were identified and included in the analysis.

The second stage of the methodology involved selecting KPIs from a subset of twenty-three publications, using sustainability criteria and the supporting data reported in these studies as the basis for selection. This ensured that the chosen indicators were both evidence-based and contextually relevant. The identified KPIs were then combined with the essential elements of BIM technology to create a dynamic workflow.

This workflow not only incorporates standard BIM functionalities but also integrates additional contextual indicators specific to the maintenance of public buildings, such as energy efficiency, material durability, and resource optimization. The final stage involved embedding these KPIs within a conceptual framework that is directly linked with BIM tools. Such integration provides a structured approach enabling the delivery of reliable, data-driven, and SM outcomes.

4 Results

Using the PRISMA technique, the study first conducts a systematic literature review to find keywords associated with building maintenance and sustainability. Figure 3's keyword clustering illustrates how most of the chosen publications fit under the first keyword, "Building Maintenance with the second primary term, "sustainable." As a result, each article and paper was examined separately for the content analysis, which will aid in the subsequent stage of determining sustainable KPIs.

To determine the KPIs, those selected papers were analysed and categorized into three components: (1) Environmental, (2) Social, and (3) Economic, which serve as inputs for sustainability metrics. According to Sijtsma et al., 2012 Adopting a long-term perspective, taking into account the global

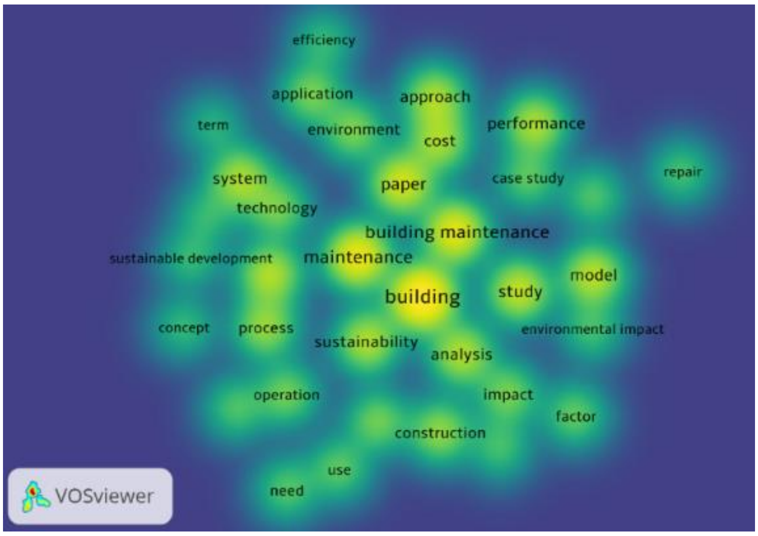

Figure 3 Visualisation of the co-occurrence of keywords by density

context, and incorporating at least these three essential components (i.e., economic, social, and environmental) is critical for sustainability assessment. For the BIM4SM framework's inputs, Table 1 provides an interpretation of the indicators and how they are quantified using the appropriate measurable units. The embedding of the sustainable KPIs will then function as a decision support system, addressing parameters such as carbon emissions, energy intensity. These can be measured through energy simulation tools and further integrated with BIM's big data/cloud platforms, in collaboration with multi-criteria analysis, to arrive at a single decision model.

Table 1 Shows the Sustainable input KPI's & indicators

Dimension	***Indicators***	***Source(s)***
Environmental	• *Operational Energy Intensity (kWh/m^2/yr)* • *Operational Carbon Intensity (kgCO_2e/m^2/yr)* • *Water Use Intensity (L/m^2/yr)* • *Maintenance Waste Rate & 3R performance (reduce–reuse–recycle)* • *Sustainable material selection rate* • *Use of Non-Destructive Testing (NDT) for inspections*	(Bakar *et al.*, 2021) ,*Azar et al. (2016),* (Hauashdh *et al.*, 2022b)(Pomè *et al.*, 2023)
Economic	• *O&M phase share of total lifecycle cost (≈75–80%)* • *Maintenance cost per m^2* • *Budget adherence/variance* • *Unplanned downtime/availability (hours offline per system)* • *Lifecycle cost (LCC) optimization*	(Hauashdh *et al.*, 2022b) (Bakar et al., 2021) (D'Orazio etal., 2024)
Social / Occupant	• *Occupant satisfaction with maintenance (quality, timeliness)* • *Health & safety indicators (incidents/near-misses)* • *User behavior/engagement in maintenance (e.g., defect reporting)*	(Hauashdh *et al.*, 2022b)*;* (Adegoriola *et al.*, 2023)*;* (Pomè *et al.*, 2023)

Table 2 describes how BIM tools such as IFC work together to build a closed-loop feedback learning workflow that converts static, linear models into predictive, optimized models using IoT, digital twins, and related technologies. To support this point, a summary of each element identified and its function within BIM is presented in Table 2.

Table 2 BIM Integration Components in SM

Integration Component	***Function in BIM Lifecycle***	***Source Paper(s)***
Autodesk Revit	*3D modelling, design coordination, and as-built documentation*	*(Chen and Tang, 2019); Abubakar et al. (2021)*
Navisworks	*Clash detection, 4D scheduling, and visualization of construction and maintenance sequences*	*(Chen and Tang, 2019)*
ArchiCAD / Bentley Systems	*Alternative BIM platforms for global adoption*	(Volk *et al.*, 2014)
CostX, Vico Office	*5D cost estimation, linking model data with cost databases*	(Sheng *et al.*, 2016) *(Chen and Tang, 2019)*
IFC (Industry Foundation Classes)	*Data interoperability across different BIM software and stakeholders*	(Volk *et al.*, 2014)
COBie	*Capturing and transferring O&M data into facilities management systems*	(Bakar *et al.*, 2021)
GIS-BIM Integration	*Linking building and urban-scale data for sustainability and facility management*	*(Sarigul and Gunaydin, 2025)*
IoT Sensors	*Real-time monitoring of energy use, HVAC performance, and equipment status*	(Islam *et al.*, 2020)
Digital Twins	*BIM + IoT + analytics for predictive maintenance and cost reduction*	(Sobowale *et al.*, 2023)*; (Sarigul and Gunaydin, 2025)*
Cloud Platforms / Big Data	*Storage, collaboration, and multi-user real-time data access*	(Hauashdh *et al.*, 2022b)
Energy Simulation Tools *(e.g., one click LCA, Design Builder)*	*6D BIM: Assessing energy use, CO_2 emissions, and sustainability performance*	(Pomè *et al.*, 2023) *(Sarigul and Gunaydin, 2025)*
Reliability Modelling (Weibull distribution)	*Predicting failure probability, scheduling preventive maintenance*	*(Chen and Tang, 2019)*
Lifecycle Costing Tools	*Economic performance analysis, lifecycle cost optimisation*	(Hauashdh *et al.*, 2022b)

The conceptual framework BIM4SM (Figure 4) functions as an operating ecosystem that integrates sustainability considerations into building maintenance across the lifecycle. The framework has been structured into four layers: foundation, workflow, impact, and learning.

Foundation layer (inputs): It consists of three components. First, sustainable KPIs were grouped into environmental (energy consumption, carbon emissions, waste and water efficiency), social (occupant comfort, health and safety, workforce training), and economic (lifecycle cost efficiency, maintenance savings, time efficiency) categories. Second, BIM technology components were identified, including Revit, Navisworks, ArchiCAD, CostX, IFC, COBie, IoT sensors, digital twins, cloud platforms, and energy simulation tools. Third, contextual factors such as budget limits, policy requirements, funding availability, and workforce skill sets were considered.

Workflow layer (processes): It explains how these inputs are operationalized. Data integration allows real-time sustainability KPIs to be embedded in BIM. Predictive maintenance is supported through AI/ML-based detection models. Decision support is provided through multi-criteria calculations, simulations, and optimization routines. Collaboration is supported through digital dashboards, cloud platforms, and shared data environments.

Impact layer (outputs): It presents the expected outcomes of this workflow. These include extended asset life, reduction in lifecycle carbon emissions, lower operational costs, energy optimization, improved occupant comfort, and alignment with SDG-related policy targets.

Learning layer (feedback and continuous improvement): It provides the final element of the framework. This includes periodic review and monitoring of metrics, updating of targets and processes, and compliance verification through documentation and regular audits. The feedback loop enables continuous refinement of the framework and supports its application in future building maintenance cycles.

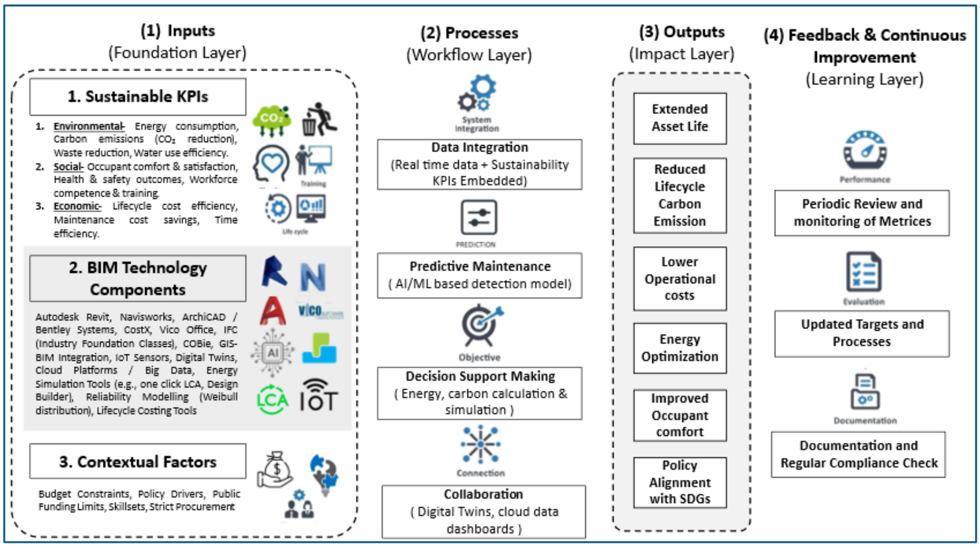

Figure 4 BIM4SM Conceptual Framework

5 Discussion

This study contributes towards a shift in the field of sustainable building maintenance using emerging technologies and tools that are already available to enhance practices and build a better ecosystem for building occupants. The proposed framework offers a potential solution for problems such as technical interoperability and static, linear, or overly complex models, as discussed by Wong and Zhou (2015), and the need for a standardized feedback loop framework as noted by Matarneh et al. (2019). By structuring the BIM4SM framework into four layers (foundation, workflow, impact, and learning), the results demonstrate how sustainability KPIs can be systematically embedded into BIM-enabled processes, producing measurable outcomes related to efficiency, resilience, and lifecycle performance. It aims at bridging the gap between the existing literature and current industry needs through a proper feedback mechanism. These studies have demonstrated the shortcomings of previous case studies by highlighting the gaps and difficulties in sustainable maintenance, particularly those pertaining to the integration of environmental and sustainable indicators, the underutilization of cutting-edge technologies and tools, and the lack of a mitigation conceptual roadmap. The results of this study respond directly to these shortcomings by demonstrating that a layered BIM4SM framework can integrate environmental, social, and economic KPIs with digital tools such as IoT, digital twins, and simulation platforms, thereby providing a more holistic and proactive approach.

The study's methodological constraints are limited as it was conducted during the O&M phase, and it focused primarily on sustainable indicators as a goal while integrating cutting-edge technologies and methods. The major findings of this study will serve as a foundation for future scholars, experts, and facility managers working in the fields of sustainability, building management, and governance in general.

6 Conclusions

This study reviewed the current state of SM in the global context and examined its integration with developing BIM technologies. A total of 81 publications from 2005–2025 were analysed, highlighting the need to embed sustainability KPIs into BIM-enabled workflows. The findings confirm that BIM should not be viewed solely as an architectural 3D modelling tool, but rather as a platform with broader capabilities in cost, scheduling, energy, and lifecycle optimisation. The proposed BIM4SM framework organises these capabilities into a structured approach, providing a foundation for sustainable building upkeep, particularly for public institutional buildings. The research scope was limited to the operation and maintenance (O&M) phase, focusing primarily on sustainability indicators in relation to advanced digital tools. As a result, other building typologies or individually maintained structures may not fully benefit from the framework. This is ongoing research work; hence, future work aims to validate the framework through case studies on real public buildings, demonstrating its application and refining its processes through practical feedback. Such extensions will help establish BIM4SM as a standard workflow model, promoting collaboration between facility managers, researchers, and practitioners in the fields of BIM and sustainable building maintenance.

Conflicts of Interest

The authors declare no conflict of interest.

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