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A FRAMEWORK OF ATTRIBUTES FOR AS-BUILT BIM MODELS: A SYSTEMATIC REVIEW

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Afiqah R. Radzi,
Ph.D. Candidate, Department of Building Surveying, Faculty of Built Environment, Universiti Malaya, Kuala Lumpur, Malaysia
nurafiqah279@gmail.com

Nur Farhana Azmi,
Senior Lecturer, Centre for Building, Construction & Tropical Architecture (BuCTA), Department of Building Surveying, Faculty of Built Environment, University Malaya, Kuala Lumpur, Malaysia
farhanazmi@um.edu.my

Syahrul Nizam Kamaruzzaman,
Professor, Centre for Building, Construction & Tropical Architecture (BuCTA), Department of Building Surveying, Faculty of Built Environment, Universiti Malaya, Kuala Lumpur, Malaysia
syahrulnizam@um.edu.my

Rahimi A. Rahman,
Associate Professor, Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Kuantan, Malaysia
Visiting Professor, Faculty of Graduate Studies, Daffodil International University, Dhaka, Bangladesh
arahimirahman@ump.edu.my

SUMMARY: *Accurate digital twins are crucial in improving facility management. However, facility owners often encounter inaccurate digital twins due to incorrect as-built Building Information Modeling (BIM) models. By understanding the attributes of correct as-built BIM models, it is possible to reduce the production of inaccurate digital twins. This study aims to establish a framework of attributes for developing as-built BIM models. To achieve this, a systematic review of published articles using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) technique was conducted to identify relevant attributes for developing as-built BIM models. Next, a comprehensive conceptual framework was established for the development of as-built BIM models. Through the analysis of 50 articles, nine attributes of as-built BIM models were identified and grouped into three categories: data quality, data interoperability, and data security. Data quality encompasses accuracy, completeness, ease of understanding, coordination, consistency, and up-to-date. Data interoperability includes accessibility and compatibility, and data security pertains to security. The study findings could provide valuable guidance to industry practitioners and policymakers in developing strategies for producing correct as-built BIM models, ultimately improving the production of accurate digital twins and enhancing overall facility management.*

KEYWORDS: *building information modeling, as-built bim, digital twin, systematic review, facilities management.*

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1. INTRODUCTION

A digital twin is a virtual representation of a constructed facility that spans its entire lifecycle (Qi & Tao, 2018). It consists of three fundamental components: the physical twin (the constructed facility), the digital model (its virtual counterpart), and the linkage that connects them (Glaessgen & Stargell, 2012). Digital twins are invaluable for facility managers, as they enable the simulation and evaluation of different scenarios to predict and manage challenges throughout a facility's lifecycle (Nasaruddin et al., 2018). Digital twins significantly enhance facility management by providing essential information, such as geometry, component details, and operational parameters stored in as-built building information modeling (BIM) models (Pishdad-Bozorgi et al., 2018). Producing accurate digital twins of facilities requires correct as-built BIM models (Khajavi et al., 2019). Incorrect as-built BIM models lead to inconsistencies between the physical facility and its digital twin, resulting in flawed analyses and misguided decisions regarding maintenance, renovations, or operations (Klein et al., 2012). The accuracy of digital twins is heavily dependent on the correctness of the underlying data. Incorrect as-built BIM models compromise digital twins' ability to predict performance and identify potential issues (Akcamete et al., 2009). Incorrect as-built BIM models can lead to ineffective facility management processes, with maintenance schedules potentially neglecting critical areas or misallocating resources, thereby increasing operational costs and the risk of downtime (O'Connor et al., 2004). Therefore, ensuring the correct development of as-built BIM models is crucial for producing accurate digital twins. The accuracy of a digital twin is directly tied to the correctness of the as-built BIM model, underscoring the importance of meticulous BIM model development for effective facility management.

As-built BIM models are often incorrect when delivered at project handover (Khemlani, 2011; Kassem et al., 2015; Sadeghi et al., 2019). This issue primarily arises due to inadequate processes for updating BIM models with actual data (Gu and London, 2010) and uncertainties regarding the qualifications of those managing and inputting data (Becerik-Gerber et al., 2012). Additionally, minimal involvement of facility managers throughout the project lifecycle can contribute to these quality issues (Azhar, 2011). In response to poor-quality as-built BIM models, stakeholders sometimes consider redeveloping the as-built BIM model. East and Brodt (2007) noted that contractors are often hired to survey existing facilities and create more correct as-built BIM models. This redevelopment process may involve advanced technologies, including 3D point clouds from digital cameras (Bhatla et al., 2016; Klein et al., 2012) or automated creation from laser scanner data (Kim et al., 2016; Wang et al., 2015). Despite the potential benefits of redevelopment, the process is often costly (East and Brodt, 2007). This expense can deter stakeholders from pursuing it, leading them to continue using flawed as-built BIM models for facility management, which can have significant consequences. For example, maintenance activities based on flawed BIM models might overlook critical issues, leading to potential safety hazards or operational disruptions. Therefore, there is a clear need to develop appropriate approaches to ensure the development of correct as-built BIM models. By addressing these issues, the correctness of as-built BIM models can be improved, enhancing the effectiveness of facility management processes.

Over the past few decades, there has been a growing body of literature on implementing BIM across different nations. Despite this progress, a significant challenge remains: the lack of clarity on determining when as-built BIM models are ready for handover, leading to incorrect deliverables (Sadeghi et al., 2019; Cavka et al., 2018). Instead of developing as-built BIM models from scratch (Usmani et al., 2020), leveraging existing research can provide an overarching view of the essential attributes that define correct as-built BIM models. Given the extensive research in this field, it is imperative to establish a comprehensive list of attributes specific to as-built BIM models. Understanding these attributes promotes better integration and interoperability between different systems and stakeholders involved in facility management. This ensures seamless data flows between the as-built BIM model and the digital twin. Stakeholders familiar with the attributes of as-built BIM models can verify that the digital twin accurately represents the constructed facility. This verification builds confidence that the digital twin is produced on correct data, enhancing its accuracy in predicting facility behavior and performance over time. Knowledge of as-built BIM attributes empowers stakeholders to monitor and optimize facility performance through accurate digital twins. Stakeholders can implement proactive maintenance strategies, identify potential issues before they escalate, and optimize facility utilization. Predictive analytics enabled by the digital twin allow timely interventions, reducing downtime and improving facility reliability (Agostinelli and Heydari, 2022). By defining attributes of as-built BIM models, stakeholders can better assess and ensure the readiness of as-built BIM models for handover, thereby enhancing facility outcomes and efficiency across the lifecycle.

Building on the presented background, this study aims to establish a framework of attributes for developing as-built BIM models. The research methodology involves a systematic review using the PRISMA technique to analyze published articles and identify key attributes associated with as-built BIM models. Subsequently, the study constructs a conceptual framework that integrates these attributes, aiming to provide a structured approach to developing precise as-built BIM models. The study findings are anticipated to make a significant contribution to the existing knowledge by enhancing the understanding of as-built BIM model development processes. Industry practitioners and policymakers can leverage these findings to formulate effective strategies for improving the correctness of as-built BIM models. By establishing correct as-built BIM models, stakeholders can lay a solid foundation for creating accurate digital twins. These digital twins are crucial for optimizing facility management and supporting sustainable development practices within the built environment industry.

2. BACKGROUND

2.1 BIM in facility management

Accurate data throughout design, construction, as well as operation and maintenance is crucial for effective facility management (GSA, 2011). Structured management and analysis of such data can enhance decision-making processes. Ineffective facility management cost the United States approximately USD 11 billion annually (Arayici et al., 2012). These ineffectiveness are primarily due to outdated facility management processes, including manual data entry, poor quality documentation and data storage, as well as reactive maintenance practices (Anton et al., 2014; Jylha and Suvanto, 2015). Such practices often lead to cost overruns, inefficient operations, and delayed responses to owner requests, stemming from insufficient, inaccurate, or ambiguous data (Parsanezhad and Dimyadi, 2014). Conversely, data overload can be equally detrimental, making it challenging for facility managers to filter out crucial data, clogging operational databases, and reducing efficiency (Munir et al., 2020). Poorly organized data not only wastes time but also diminishes productivity (Lu, 2018). To mitigate these issues, it is crucial to define and formalize data requirements before designing a facility (Lu, 2018). This proactive approach ensures that facility managers have the data needed to make informed decisions, thereby improving the effectiveness of facility management processes.

Although the application of BIM in design and construction has progressed significantly, its use in facility management is still emerging and in its early stages of adoption (Jang and Collinge, 2020). Durdyev et al. (2021) identified several barriers preventing the industry's adoption of BIM in facility management, including contractual constraints, interoperability issues, and high upfront costs. Despite these challenges, BIM offers substantial benefits by optimizing numerous processes and serving as an archive for a facility's data, positively impacting facility management. BIM provides valuable geometry and parameters to a facility's operations database (Pishdad-Bozorgi et al., 2018). Prior research has demonstrated the potential of BIM to automate capital planning, and space management for facility managers (Becerik-Gerber et al., 2012; Weygant, 2011). Additionally, BIM enhances decision-making in facility systems analysis (Becerik-Gerber et al., 2012), commissioning procedures (Jiao et al., 2013), and preventive maintenance (Akcamete et al., 2010; Becerik-Gerber et al., 2012). Furthermore, BIM can be used to develop decommissioning and repurposing strategies (Volk et al., 2014), as well as emergency planning and response plans (Eastman et al., 2011; Zou and Wang, 2009). By leveraging BIM, the built environment industry can achieve more effective facility management processes, paving the way for innovative advancements and enhanced facility management processes.

2.2 Prior research on as-built BIM models

Facility management can benefit from the data provided by high-quality BIM models. Unfortunately, many BIM models developed during design and construction suffer from quality issues that undermine their utility post-handover (Zadeh et al., 2015). Common issues include insufficient data and the inclusion of unnecessary design and construction data, which degrades the model's utility (Motamedi et al., 2018). Furthermore, BIM models are often not updated to reflect the facility following renovation and maintenance, leading to discrepancies between the model and the facility (Tang et al., 2010; Giel and Issa, 2011; Usmani et al., 2019). Deviations caused by construction errors and scope changes add complexity in obtaining correct as-built BIM models, resulting in high costs for facility owners (O'Connor et al., 2004). To fully leverage BIM benefits for facility management, it is crucial that project teams clearly define the data requirements for their BIM models and establish a systematic process to collect and maintain this data throughout design and construction. However, a review of owner standards and guidelines reveals a lack of specific criteria to ensure the usability, effectiveness, interoperability, and maintainability of BIM models in facility management (Leygonie et al., 2022). Consequently, the industry frequently needs to make extensive modifications and improvements to BIM models before they can be effectively used for facility management. By addressing these gaps and enhancing model quality, facility managers and owners can unlock the full potential of BIM in streamlining operations and reducing long-term costs.

Researchers are actively investigating approaches to assess the quality of as-built BIM models, aiming to enhance their utility. Solihin et al. (2015) laid the groundwork by defining the characteristics of a high-quality Industry Foundation Classes (IFC) model and introducing automated rules to assess its completeness and accuracy. Building on this foundation, Lee et al. (2018) developed an approach to assess BIM data according to the diverse requirements of model view definitions (MVD). The approach can support the sharing of consistent data and ensure accuracy in the syntax and semantics of specific model views. Adding to this growing body of research, Ramesh (2016) devised a process for planning quality assurance and control during the handover of as-built BIM models. This process supports facility owners identify and manage areas of concern. Zadeh et al. (2017) contributed further by proposing an approach to assess the data in BIM models for facility management. The approach addresses different BIM data quality attributes, including completeness, accuracy, accessibility, consistency, relevancy, availability, and timeliness, categorizing them from different facility management perspectives. Leygonie et al. (2022) introduced an approach that incorporates quality assurance and control activities to ensure the usefulness of as-built BIM models for facility management. The research established a checklist to assess as-built BIM models across six dimensions: completeness, accuracy, consistency, compliance, clarity, and relevancy. Collectively, prior research highlights the crucial role of quality assessment in the BIM domain. The ongoing development and refinement of these approaches promise to enhance the utility of as-built BIM models, resulting in more effective facility management.

2.3 Positioning this study

The examination of the literature highlights a notable gap in assessing as-built BIM models during project handover, which often results in incorrect models. Consequently, project teams encounter challenges in developing as-built BIM models that meet facility management requirements. To address this issue, prior research has proposed approaches to assess the quality of as-built BIM models (Zadeh et al., 2017; Leygonie et al., 2022). Additionally, Lin et al. (2018) developed a Final As-built BIM Model Management (FABMM) system to assist facility owners in managing the final as-built BIM model post-project closeout. Although the contributions are valuable, prior research is based on specific case studies and may not be universally applicable to other projects. To bridge this gap, this study synthesizes the existing body of knowledge to develop a framework that outlines the attributes of as-built BIM models. By investigating a complete list of attributes from prior published articles, this study aims to develop a robust framework that can be widely applied across different projects. This approach ensures the correctness of as-built BIM models and supports the production of accurate digital twins for facility management.

3. METHODOLOGY

The current body of knowledge still lacks a benchmark or standard for assessing as-built BIM models during project handover. To address this gap, this study conducted a systematic literature review (SLR) of published articles to identify attributes for developing correct as-built BIM models. The main goal of SLR is to plan, identify, and assess prior research to gather and synthesize data within the subject matter (Tranfield et al., 2003). A notable advantage of SLR is its transparency, allowing other researchers to replicate the process, thereby enhancing the reliability of findings. Moreover, SLR provides an overview of a subject matter, offering researchers and practitioners evidence-based insights (Petersen, 2019; Radzi et al., 2023). By leveraging these strengths, this study aims to contribute valuable knowledge to the subject matter, supporting the development of robust standards for as-built BIM model assessment.

The SLR was conducted using the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) technique. This technique ensures evidence-based outcomes and enhances the transparency and quality of the review process (Moher et al., 2009). The structured and analytical methodology of PRISMA was a primary reason for its selection in many research, including this study (Moher et al., 2015). Moreover, PRISMA is well-established in built environment research (Radzi et al., 2021; Adaku et al., 2021). Figure 1 illustrates the review process, which involves refining an initial pool of 519 articles to a selection of 50 articles.

3.1 Database selection

The search for relevant articles was conducted using the Scopus and Web of Science (WoS) databases, which are renowned for housing the most influential peer-reviewed journals across different research fields (Chadegani et al., 2013). These databases are widely recognized and trusted in the academic community, and their use in SLR is well-documented (Mahmudnia et al., 2022). Leveraging these resources ensures the inclusion of high-quality and impactful research throughout the review.

3.2 Keywords and search string identification

Following the selection of relevant keywords, a desktop search was conducted using Scopus and WoS databases. An initial screening indicates a scarcity of research addressing the attributes of as-built BIM models. Therefore, this study purposefully reviews case studies on BIM implementation to identify the attributes. Consequently, the search string was designed to include "building information modeling," "implement," and "case study." The search was not restricted by publication year, ensuring a wide-ranging search. However, it was limited to journal articles as these are recognized as the most credible and influential sources of knowledge (Santos et al., 2017). Additionally, the search was limited to articles published in English, the standard language for high-impact scientific journals. This initial search yielded 341 articles from Scopus and 178 from WoS for the next process.

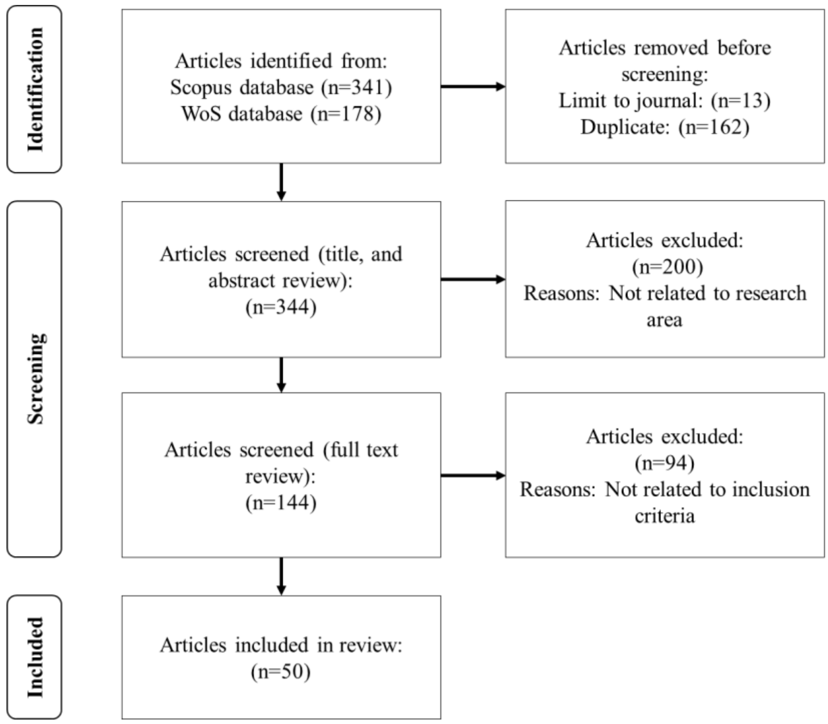

Figure 1: The SLR procedure in this study.

3.3 Screening

To ensure the inclusion of only relevant articles, a screening process was conducted. The search results were refined by screening articles that aligned with case studies on BIM implementation. This process is crucial to excluding articles that do not meet the review objectives and scope (Mok et al., 2015). The screening involved evaluating the titles and abstracts of the articles to select those pertinent to this study. As a result, 200 articles were deemed irrelevant, and 144 articles proceeded to the next step of the screening process. In the subsequent step, the content of each article was thoroughly reviewed to exclude those that did not meet the study objectives. Through this rigorous step, 50 articles were identified as valid for further investigation. This number aligns well with similar research using comparable methodologies. For instance, an SLR on the impact of extended reality on architectural education and the design process reviewed 21 articles (Kharvari and Kaiser, 2022), and an SLR on blockchain in construction management reviewed 34 articles (Mahmudnia et al., 2022). By adopting this thorough screening approach, this study ensured the selection of high-quality articles that provide valuable insights into BIM implementation, reinforcing the robustness and reliability of this study.

4. OVERVIEW OF EXISTING RESEARCH

4.1 Articles distribution

Table 1 lists the journals that were reviewed in this study. The review encompassed articles from 30 journals, with leading contributions from Construction Innovation (6 articles), Automation in Construction (4 articles), as well as Engineering, Construction, and Architectural Management (4 articles). Construction Management and Economics, as well as Buildings, each featured three articles. Smart and Sustainable Built Environment, Advances in Engineering Software, Applied Sciences, as well as Facilities each contributed two articles. The remaining journals included in the review each had one article. This overview offers valuable insights for researchers considering where to submit future research articles, helping them to identify prominent journals related to the subject matter.

Table 1: Journal titles of the selected articles.

Journal title	Number of articles
Construction Innovation	6
Automation in Construction	4
Engineering, Construction and Architectural Management	4
Buildings	3
Construction Management and Economics	3
Advances in Engineering Software	2
Applied Sciences	2
Facilities	2
Smart and Sustainable Built Environment	2
Sustainability (Switzerland)	2
Architectural Engineering and Design Management	1
Australasian Journal of Construction Economics and Building	1
Built Environment Project and Asset Management	1
Canadian Journal of Civil Engineering	1
Computers in Industry	1
Frontiers in Built Environment	1
Frontiers of Engineering Management	1
Heliyon	1
Infrastructures	1
International Journal of Construction Management	1
International Journal of Managing Projects in Business	1
Journal of Civil Engineering and Management	1
Journal of Facilities Management	1
Journal of Information Technology in Construction	1
Journal of Management in Engineering	1
Open Construction and Building Technology Journal	1
Practice Periodical on Structural Design and Construction	1
Production Planning and Control	1
Resources, Conservation and Recycling Advances	1
Tunnelling and Underground Space Technology	1

4.2 Articles by year

Fifty peer-reviewed articles that discussed BIM implementation in construction projects published between 2012 and 2024 were identified in this study. The trendline demonstrates growth in research within this field (Figure 2). On average, approximately three articles have been published annually since 2012, with a majority published after 2018. The increased number of articles reflects the growing adoption of BIM in construction projects, which has sparked interest among researchers and practitioners aiming to improve construction project performance. This trend aligns with the patterns observed by Adekunle et al. (2021) regarding BIM implementation in the construction industry. It is worth noting that the number of articles in 2024 is relatively low, with only three articles recorded as the search was finalized in April 2024.

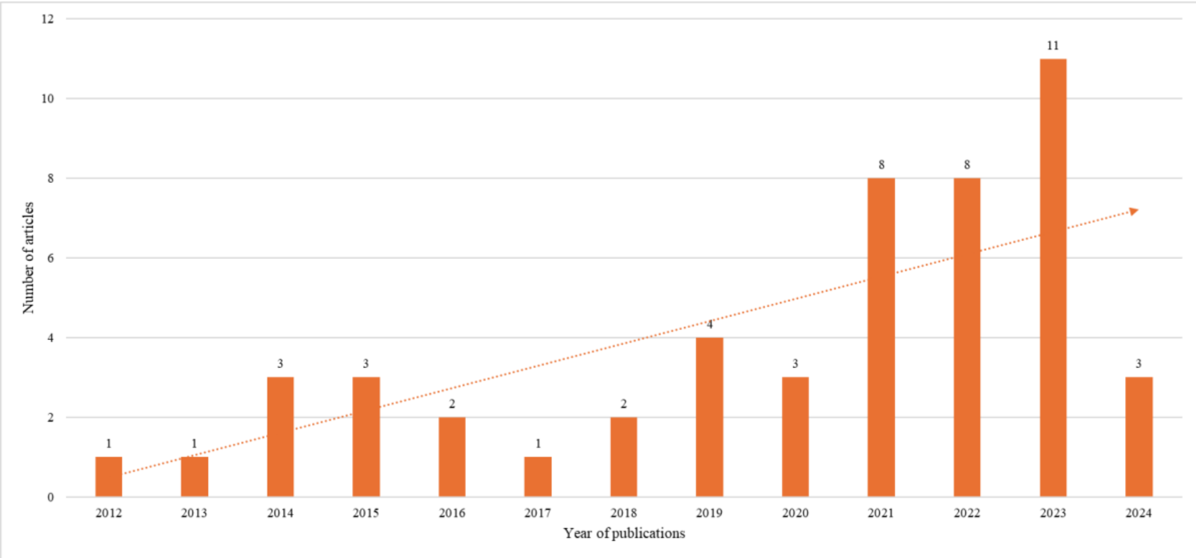

Figure 2: Publication year for the selected articles.

4.3 Co-occurrence of keywords

Keywords are words or phrases that define the research area and reflect the overall content of articles (Eck and Waltman, 2010). In this study, VOSviewer was used to analyze the co-occurrence of keywords from the selected articles. This tool conducted a keyword co-occurrence analysis using data obtained from the database. The produced map displays nodes whose distances represent the relationships between keywords (Perianes-Rodriguez et al., 2016). A shorter distance between nodes signifies a stronger association between keywords. Additionally, the size of each node indicates the number of articles containing those keywords. As illustrated in Figure 3, "building information modeling" emerges as the most significant term, reflecting its prominence in the study's focus.

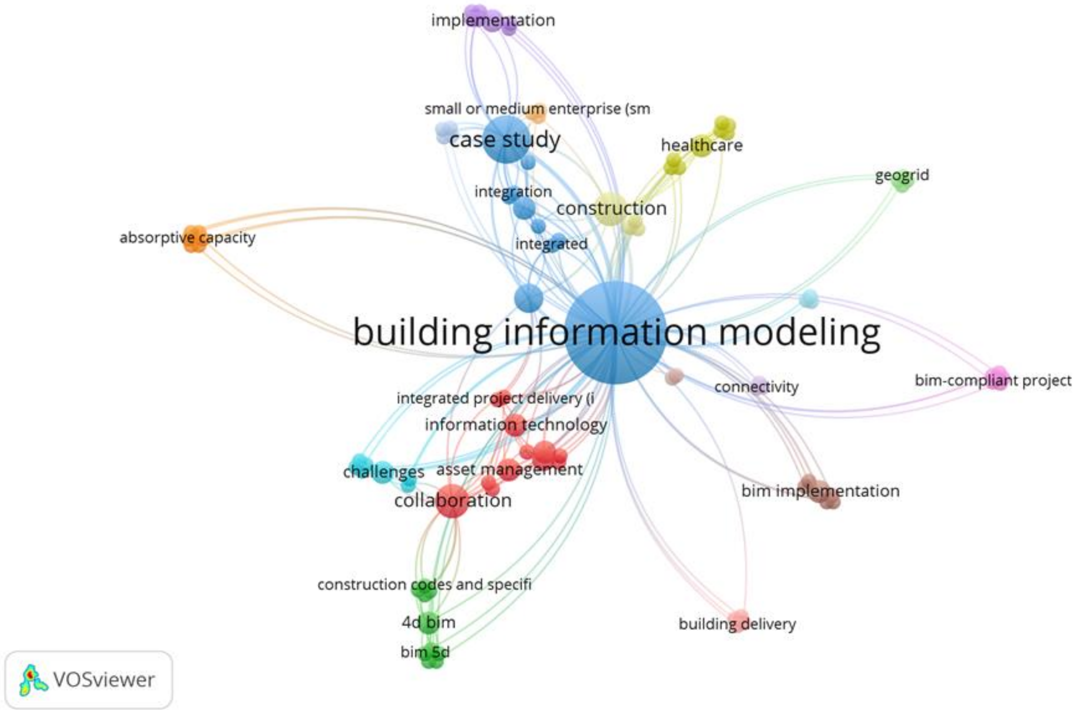

Figure 3: Keywords co-occurrence mapping.

5. ATTRIBUTES OF AS-BUILT BIM MODELS

The analysis presented in the previous section reveals a growing interest among researchers in understanding and assessing as-built BIM models. Beyond design and construction, BIM is increasingly recognized for its crucial role during operation and maintenance (Pishdad-Bozorgi et al., 2018). Ghosh and Chasey (2013) emphasized the need for clear guidelines or standards for project handover to ensure correct as-built BIM models.

This study identified nine attributes for developing as-built BIM models (see Table 2). These attributes are classified into three constructs: data quality, data interoperability, and data security. Data quality includes accuracy, coordination, completeness, up-to-date, ease of understanding, and consistency. These attributes ensure that as-built BIM models are reliable and reflect the constructed facility. Data interoperability includes compatibility and accessibility. These attributes ensure seamless integration and access to BIM data across different platforms and stakeholders. Data security includes security, highlighting the importance of protecting BIM data from unauthorized access, theft, viruses, and hacking.

Figure 4 illustrates the connection between the reviewed articles and the identified attributes of as-built BIM models. As shown in Figure 5, accuracy is the most frequently mentioned attribute, highlighting its importance in saving time and effort (Almuntaser et al., 2018). Although security is the least mentioned attribute, it remains important for safeguarding data (Abdirad, 2015). Building on these classifications, this study established a conceptual framework of attributes for developing as-built BIM models (Figure 6). This framework offers a structured approach to developing correct as-built BIM models, thereby enhancing the production of accurate digital twins.

By highlighting these attributes and their classifications, this study offers a guide for developing correct as-built BIM models. This structured approach ensures that stakeholders can rely on these models for effective facility management, ultimately contributing to the broader adoption and optimization of BIM in the built environment.

Table 2: Summary of attributes identified in selected articles.

Attributes/	**Data Quality**						**Data Interoperability**		**Data Security**
Authors	Accuracy	Coordinated	Completeness	Up to date	Easy to understand	Consistency	Compatibility	Accessibility	Security
Mani et al. (2024)								/	
Park et al. (2024)				/					
Nguyen et al. (2024)	/								
Zadeh et al. (2023)				/					
Ngbana et al. (2023)							/		
Alwee et al. (2023)	/	/	/	/					
Munianday et al. (2023)	/								/
Wang et al. (2023)	/					/			
Chen et al. (2023)		/		/					
Disney et al. (2023)				/				/	
Mohammadi et al. (2023)	/								
Costa et al. (2023)							/		
Chen et al. (2023)				/			/		
Wang et al. (2023)	/					/			
Çetin et al. (2022)							/		
Doukari et al. (2022b)		/				/			
Alirezaei et al. (2022)				/					
Doukari et al. (2022a)		/				/			
Suprun et al. (2022)	/			/					
Disney et al. (2022)	/	/		/			/	/	
Arayici et al. (2022)	/	/		/				/	
Savaşkan and Özener (2022)							/		
Siebelink et al. (2021)			/				/		
Keskin et al. (2021)		/						/	
Alshorafa and Ergen (2021)		/		/			/		

Wang and Zhang (2021)	/		/			/			
Li et al. (2021)	/		/		/		/		
Shafiq (2021)		/	/	/					
Jasiński (2021)	/			/					
Lindblad and Karrbom Gustavsson (2021)		/					/	/	
Aibinu and Papadonikolaki (2020)		/							
Liao et al. (2020)	/			/					
Harris and Alves (2020)			/		/				
Dowsett and Harty (2019)					/				
Wanigarathna et al. (2019)							/	/	
Neves et al. (2019)	/		/				/		
Koseoglu et al. (2019)		/		/			/	/	
Almuntaser et al. (2018)	/		/						
Matthews et al. (2018)		/			/			/	
Sackey and Akotia (2017)		/				/	/		
Gledson (2016)							/		
Ahn et al. (2016)		/					/	/	
Kassem et al. (2015)	/						/		
Cavka H.B. et al. (2015)	/		/		/	/			
Poirier E. et al. (2015)		/	/			/			
Clevenger and Khan (2014)		/		/					
Chen and Luo (2014)			/	/			/		
Chien et al. (2014)	/			/					/
Porwal and Hewage (2013)	/		/						
Azhar et al. (2012)	/					/			
Total	20	17	12	18	5	9	18	10	2

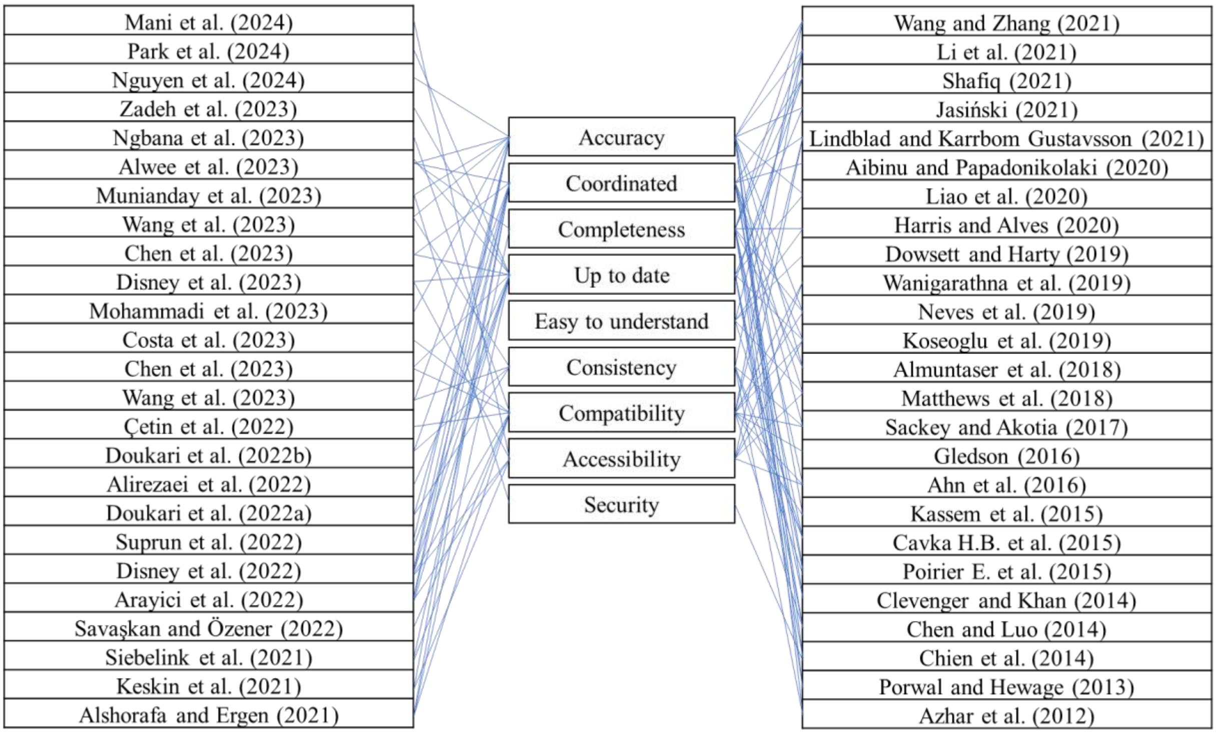

Figure 4: Connection between the selected articles and the identified attributes.

5.1 Data quality

5.1.1 Accuracy

Accuracy is the state of being precise without any mistakes. Du et al. (2014) define accuracy as the degree to which an as-built BIM model precisely reflects the true state of a facility. Similarly, Zadeh et al. (2017) emphasize that an as-built BIM model is considered accurate when all essential elements precisely represent the constructed facility. According to Zadeh et al. (2015), accurately placing an element in an as-built BIM model means not only identifying its location but precisely pinpointing its position within the assigned space. Almuntaser et al. (2018) highlight that accurate as-built BIM models can save facility managers significant time. Conversely, inaccurate models can hinder facility management, leading to issues with aesthetics, structural integrity, and wasted time locating poorly digitized elements (Kielhauser et al., 2017; Jurgen et al., 2018, Esfahani et al., 2021).

Producing accurate as-built BIM models presents several challenges. Azhar et al. (2013) note that different standards across organizations can lead to inaccuracies due to the lack of unified protocols. Jasinski et al. (2021) observe that the required level of accuracy can differ, with inexperienced facility owners often demanding the highest accuracy in all aspects, posing a substantial challenge in developing as-built BIM models. Addressing this issue, Li et al. (2021) recommend verifying as-built BIM model accuracy post-construction, and Wang and Zhang (2021) advocate for continuous quality assurance methods. Liao et al. (2020) mention that BIM modelers should develop accurate as-built BIM models for facility owners, and Esfahani et al. (2021) found that training BIM modelers can significantly enhance accuracy and precision by 260 percent and 330 percent on average. In summary, ensuring the accuracy of as-built BIM models is crucial for facility management. By adopting standard protocols, verifying models post-construction, implementing continuous quality assurance, and investing in training, practitioners can enhance the accuracy of as-built BIM models, leading to more effective facility management.

Figure 5: Frequency of attributes identified from the selected articles.

5.1.2 Coordinated

Coordinated refers to organizing all elements to function seamlessly together. BIM streamlines the design process by merging multiple systems, allowing for the identification and resolution of potential clashes. Multidisciplinary BIM coordination involves merging models from different systems, such as architecture, structural, mechanical, electrical, and plumbing (MEP), ventilation, and prefabrication, to identify potential clashes. This process includes conducting coordination meetings, issuing clash reports, compiling lists of model elements, and verifying the accuracy and precision of available data. When developing as-built BIM models, it is crucial to ensure these models are coordinated (Poirier et al., 2015). As Poirier et al. (2015) highlighted, coordinated as-built BIM models are essential for effective facility management. Lindblad and Karrbom Gustavsson (2021) further emphasized that coordinated as-built BIM models incentivize stakeholders to use them for facility management, leading to increased productivity and reduced costs.

However, inconsistencies in the coordinated as-built BIM models can lead to waste and cost overruns (Koseoglu et al., 2019). To address this, Shafiq (2021) recommended that the coordination process involve design consultants leading the clash detection exercise, followed by BIM consultants ensuring the final model is fully coordinated and clash-free. Furthermore, appointing a BIM coordinator to oversee the interaction between the architectural, structural, MEP, fire safety, and other systems is crucial. The BIM coordinator's role is crucial in developing a model where no systems clash, ensuring the smooth development of as-built BIM models. By focusing on effective BIM coordination, facility management can achieve greater efficiency, foster better collaboration among stakeholders, and realize significant cost reductions. Embracing these practices ensures that as-built BIM models are correct and valuable for facility management.

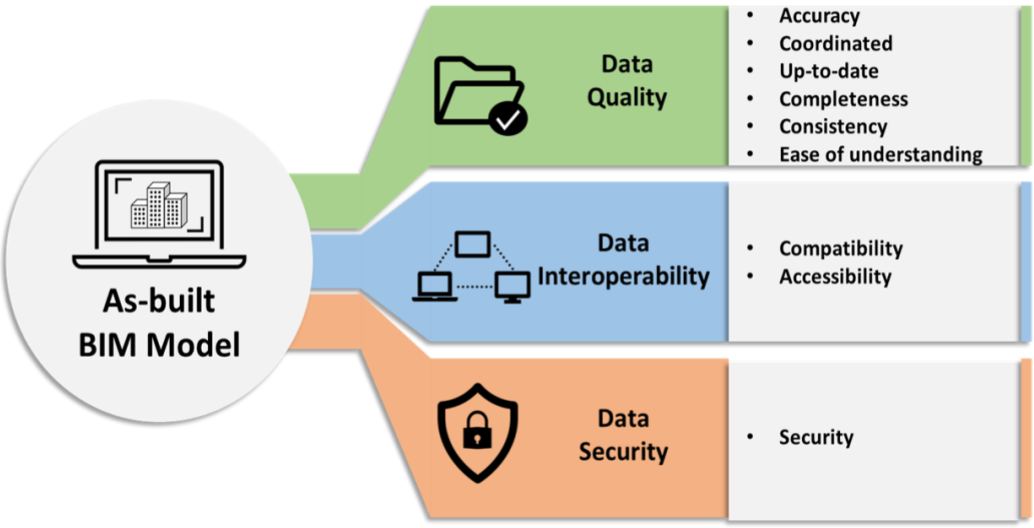

Figure 6: The framework of attributes for as-built BIM models.

5.1.3 Up-to-date

This study defines up-to-date as incorporating the latest data. Relying on outdated data can be as detrimental as not using any data at all. Moreover, maintaining up-to-date data is a legal responsibility (American Bar Association, 2006). Ensuring that every workstation operates with up-to-date data allows employees to perform duties effectively. Up-to-date data not only enhances job performance but also improves worker safety by reducing the likelihood of incidents through appropriate procedures and work instructions.

In the context of as-built BIM, models are continually updated throughout construction by incorporating as-built data and integrating it into facility management manuals and documents. This integration with an organization's current facility management procedures ensures that the developed as-built BIM models can support facility management processes (Shafiq 2021). Providing stakeholders with access to the most up-to-date as-built BIM models helps prevent misunderstandings and conflicts. Moreover, up-to-date BIM models enable swift decision-making and problem-solving, keeping facility management processes on track and minimizing delays.

An updated as-built BIM model can serve as the single and reliable source of truth for stakeholders. However, continually updating the as-built BIM models to create new versions can lead to version control issues (Chien et al., 2014). Additionally, questions remain about who is qualified to update and load data into BIM models (Becerik-Gerber et al., 2012). The industry also faces a challenge of qualified BIM professionals, who are in high demand and often command higher salaries, leading to higher facility management costs. To maintain up-to-date data in as-built BIM models, it is recommended that BIM professionals ensure timely updates (Liao et al., 2020). By maintaining up-to-date data, facilities can achieve higher efficiency and safety, leading to successful outcomes and satisfied stakeholders.

5.1.4 Completeness

Completeness refers to having all required data with nothing missing. An as-built BIM model achieves completeness when all required elements are present and reflect the constructed facility (Zadeh et al., 2017). A complete as-built BIM model enables the simultaneous exploration of complex architectural spaces, system coordination through 3D modeling, rapid prototyping of details, and the extraction of 2D documentation (Neves et al., 2019; Shafiq, 2021).

However, issues arise when as-built BIM models are incomplete (Harris and Alves, 2020). Missing elements in as-built BIM models that do not represent the constructed facility require significant effort to model (Zadeh et al., 2015). Integrating IoT with incomplete as-built BIM models can hinder effective digital representations of sensor objects and measured spatial elements (Moretti et al., 2020). Inaccurate analyses and miscomputation of data are other consequences of incomplete as-built BIM models, which prevent repurposing for facility management (Stumpf et al., 2011; Cavka et al., 2017).

Several approaches have been proposed to address these completeness issues. Integrating fully standardized and structured construction codes is one effective approach (Chen and Luo, 2014). Continuous quality assurance through manual checking and point cloud technology is another approach to ensure completeness (Wang and Zhang, 2021). Additionally, a checklist can ensure that all required data is included in the models. For instance, Leygonie et al. (2022) developed a checklist approach during project handover to deliver useable as-built BIM models for operation and maintenance. By adopting these approaches, practitioners can ensure the completeness of as-built BIM models, thereby enhancing their utility for different applications, including facility management.

5.1.5 Consistency

Consistency refers to the uniformity, reliability, and stability of data over time. At its core, BIM is about managing and using data effectively. One key benefit of BIM is its ability to maintain consistent data throughout a facility's lifecycle, preventing data loss as a facility transitions from design to construction and, ultimately, operation and maintenance. For as-built BIM models to reach their full potential, the data input must be consistent. Inconsistencies between the semantic and geometric elements of as-built BIM models can lead to data interpretation issues for facility owners and managers (Daum and Borrmann, 2013). Furthermore, the absence of standard protocols across different organizations can lead to variations in BIM model development, potentially leading to incorrect as-built BIM models if not properly detected (Azhar et al., 2012).

Achieving consistency in as-built BIM models requires continuous quality assurance, which can be supported by manual checking and point cloud technology (Wang and Zhang, 2021). To further ensure consistency, Kim et al. (2018) developed a checklist to assess the consistency of as-built BIM models with the constructed facility during the construction documentation process. Establishing modeling standards or guidelines by local or industry groups is a potential solution to the consistency issue. It is crucial to enforce these standards and ensure team members adhere to them in their BIM modeling processes. Regular quality control checks on BIM models can help ensure compliance with the standards. This practice encourages BIM professionals to develop the habit of using the appropriate standards. Alternatively, model checkers can be employed to verify whether an a-built BIM model adheres to a specific set of standards. By adopting these approaches, the built environment industry can enhance the correctness of as-built BIM models, ensuring that they provide maximum throughout the lifecycle of a facility.

5.1.6 Ease of understanding

As-built BIM models are easy to understand when users can link all necessary elements to the constructed facility (Zadeh et al., 2017). Easy-to-understand as-built BIM models enhance facility management processes through better management processes, streamlined technical explanations to relevant personnel, and reduced errors (Li et al., 2021). Additionally, integrating color-coded spool sheets with as-built BIM models increases transparency for laborers during installation (Harris and Alves, 2020). Dowsett and Harty (2019) emphasized that easy-to-understand as-built BIM models are crucial when explaining 3D spaces to stakeholders, enabling effective planning and minimizing on-site errors.

Conversely, as-built BIM models that are difficult to understand can lead to inaccurate representations of constructed facilities. The primary challenge in developing easy-to-understand as-built BIM models is often the lack of in-house expertise. This deficiency can lead to ineffective facility management, thereby affecting profitability. To enhance stakeholders' understanding of as-built BIM models, employing color schemes to represent different elements such as individual room floor and ceiling materials, correlated color temperature requirements, floor minimum structural strengths, and fire alarm zoning, proves beneficial (Manning and Messner 2008). This approach not only clarifies the model but also improves communication and coordination among stakeholders, ensuring successful facility management.

5.2 Data interoperability

5.2.1 Compatibility

Compatible refers to the seamless integration of different software, tools, and devices by stakeholders. Ensuring all stakeholders have access to compatible as-built BIM models is crucial for effective facility management (Matthews et al., 2018). Furthermore, as-built BIM models should be compatible with multiple data applications such as engineering drawings, photographs, and images, to better present available data (Chen and Luo, 2014). Sharing a unified as-built BIM model across all stakeholders is crucial to ensure consistency, and using BIM-compatible software supports this collaborative process (Eastman et al., 2011). One of the main risks of adopting BIM is the lack of understanding of software compatibility, which can lead to inadequate model quality and suboptimal outcomes (Ahn et al., 2016). Incompatible as-built BIM models can lead to issues, such as only transferring graphical data from one platform to another without accompanying non-graphical data (Sackey and Akotia, 2017). This lack of compatibility across software packages is a challenge, particularly for small and medium-sized enterprises (H&Vnews, 2013). Additionally, compatibility issues can lead to delays in transferring data from an as-built BIM model into facility management systems during project handover (Pishdad-Bozorgi et al., 2018). Therefore, it is recommended that guidelines include data formatting requirements that are compatible with the selected facility management system and should be communicated with the project team during project planning.

To overcome compatibility issues, improvements are being made to improve the interoperability of data exchange through open data standards such as the IFC. As a result, the International Alliance of Interoperability (IAI) has developed IFC standards to generate neutral file formats and support data exchange between CAD, estimation, and other software. Despite these efforts, the industry continues to strive to address compatibility issues associated with IFC-type files (Thurairajah & Goucher, 2013). If as-built BIM models are incompatible, project teams may face the risk of data loss during the transfer process. Thus, it is crucial to establish infrastructure support focusing on open file exchange formats, like IFC, to ensure seamless data interoperability and maintain data integrity across the lifecycle of a facility.

5.2.2 Accessibility

Accessibility refers to the ease of use and understanding. When data is accessible, it can be read, received, and comprehended by its intended users. According to the executive director of the buildingSMART alliance™, there are ten principles of as-built BIM models, including ensuring that data is externally accessible yet protected, as well as using international standards and cloud storage to ensure long-term accessibility (Kubba, 2012). As-built BIM models accessible by stakeholders create a coordinated environment that minimizes errors by eliminating conflicting information. With stakeholders having access to all necessary data regardless of their location, there are no excuses for not being aware of a facility's condition. This improved communication enables better decision-making and reduces the likelihood of costly disputes. Additionally, critical and sensitive data within as-built BIM models are securely managed, ensuring access is limited to authorized personnel only (Cox and Terry, 2008). However, it is crucial to recognize that as-built BIM models also pose the risk of data misuse, underscoring the need for continuous safety improvement. By maintaining robust security measures, organizations can ensure the benefits of as-built BIM models are fully realized while safeguarding sensitive data.

5.3 Data security

5.3.1 Security

Security in the context of as-built BIM models means safeguarding data from threats and unauthorized access. Data security involves protecting sensitive data throughout its lifecycle, preventing unauthorized access, corruption, and theft. As-built BIM models often contain sensitive data, such as intellectual property, financial details, and personal information. Compromised data can lead to serious consequences such as financial loss, loss of trust, and reputational damage. Additionally, to prevent political and commercial espionage, security is crucial for as-built BIM models of facilities with high national value, such as military sites, police stations, prisons, large bridges, power plants, as well as office and industrial buildings.

The British Standards Institution (BSI) has released the "specification for security-minded information modeling; digital built environments and smart facility management (PAS 1192-5)." By adhering to the guidelines, BIM users can safeguard key data, maintain stakeholder confidence, and mitigate the risks posed by cyber-security breaches. Olatunji (2011) highlighted the potential legal consequences of cybersecurity breaches when sharing as-built BIM model data across different geographical locations, advocating for appropriate and specific security measures. Skandhakumar et al. (2018) recommended using an access control policy language to automatically link individuals, as-built BIM model elements, conditions of security breaches, and associated consequences. However, determining responsibility for data breaches in as-built BIM models remains complex, particularly when multiple stakeholders are involved.

Security must be integrated into organizations at every level to fully protect as-built BIM models. It is also crucial that the entire supply chain adopts a security-conscious mindset, with all stakeholders supporting the data security procedures in place. As-built BIM models are valuable assets containing sensitive data that could affect stakeholders in different ways. Preventing data breaches involves using cutting-edge technology to protect data and being aware of how and by whom the data is accessed. Therefore, facility owners must establish data protection systems for as-built BIM models. Embedding security into organizational practices ensures that as-built BIM models are accessible yet protected. In other words, safeguarding as-built BIM models is crucial to maintaining the integrity and trust of facility management processes. By adopting comprehensive security measures and fostering a culture of security awareness, organizations can effectively protect sensitive data and mitigate the risks associated with data breaches. This proactive approach ensures that as-built BIM models are not only valuable assets but also secure and reliable resources for all stakeholders.

6. IMPLICATIONS

6.1 Theoretical implications

The theoretical implications of this study are substantial and multifaceted. Firstly, it enriches the body of knowledge by establishing a list of attributes for as-built BIM models. Ensuring these attributes are present is key to determining the readiness and success of as-built BIM models during project handover. A clear understanding of attributes that significantly influence the development of as-built BIM models is crucial for developing correct as-built BIM models. Correct as-built BIM models can, in turn, produce accurate digital twins of the constructed facility, which offers numerous advantages, including increased energy efficiency through a balanced distribution of heat and light (Kaewunruen et al., 2018). Additionally, digital twins provide valuable data on facility management requirements, supporting stakeholders in enhancing overall facility efficiency. This study supports prior research findings that there is a notable lack of comprehensive checklists and procedures to assess the correctness of as-built BIM models (Leygonie et al., 2022). As the first study to systematically identify the attributes of as-built BIM models by analyzing peer-reviewed articles, it addresses this gap. The methodology employed can also serve as a framework for other researchers in establishing attributes in different research areas. In summary, this study not only contributes to the existing knowledge but also provides practical insights for improving the correctness of as-built BIM models, ultimately enhancing the production of accurate digital twins.

6.2 Practical and managerial implications

Regarding practical and managerial implications, industry practitioners can greatly benefit from the identified attributes in this study to enhance the development of as-built BIM models. By prioritizing these nine attributes, practitioners can ensure the correctness of their as-built BIM models, leading to the production of more accurate digital twins. Additionally, facility owners can leverage the study findings to develop policies aimed at preventing increased costs and rework caused by incorrect as-built BIM models. Prior research has demonstrated that incorrect as-built BIM models lead to higher costs and extensive rework during operation and maintenance (Foster, 2011; Michael et al., 2004). By adhering to the attributes established in this study, policies can be formulated to avoid pitfalls of incorrect as-built BIM models, ultimately safeguarding profits and minimizing inefficiencies. Furthermore, the findings have significant implications for policymaking. Policymakers can implement measures, such as developing national regulations, to ensure that as-built BIM models are created by these attributes. Enhanced policy support and standardized BIM practices would promote the development of correct as-built BIM models, encouraging organizations to define BIM workflows and establish organizational-level BIM platforms (Tu et al., 2021). By integrating these attributes in their practices, practitioners, managers, and policymakers can collectively enhance the correctness of as-built BIM models, leading to the production of accurate digital twins and driving positive outcomes to facility management processes.

7. CONCLUDING REMARKS

Correct as-built BIM models hold immense potential for downstream data users, such as facility owners and managers, by generating accurate digital twins of constructed facilities and enhancing facility management processes. However, the current body of knowledge has primarily focused on redeveloping as-built BIM models using different technologies rather than developing correct as-built BIM models from project inception. Moreover, facility owners face challenges in assessing the correctness of delivered as-built BIM models, highlighting a need for further research. To address this gap, this study presents a list of attributes for as-built BIM models and a conceptual framework, making it accessible and beneficial to industry practitioners and researchers alike.

This study offers an SLR of journal articles to identify attributes for developing correct as-built BIM models. A thorough review of 50 journal articles revealed attributes grouped into three categories: data quality, data interoperability, and data security. Data quality includes accuracy, completeness, ease of understanding, coordinated, consistency, and up-to-date. Data interoperability includes accessibility and compatibility. Data security includes security. By providing a comprehensive overview of these attributes, the study contributes to the current body of knowledge. Industry practitioners and policymakers can leverage the study findings to develop strategies for developing correct as-built BIM models, ultimately leading to the production of accurate digital twins and promoting effective facility management.

Despite its valuable contributions, this study has several limitations that should be considered. First, the study was limited to journal articles. Future research may incorporate other document types to broaden the scope. Additionally, the literature search employed a limited set of keywords, which may not have captured the full extent of relevant research areas. Future research could use a broader range of keywords to extend the coverage. Although this study includes advice on how to achieve the stated qualities of as-built models based on the recommendations from the reviewed articles, information from external sources was not incorporated. Consequently, the study is limited in providing comprehensive strategies for each attribute. Future research should focus on developing specific strategies for achieving each attribute and exploring alternative means of handling as-built information, such as unstructured document databases. Nevertheless, this study highlights the importance of developing correct as-built BIM models from project inception. By addressing the identified gaps and limitations, future research can be built on these study findings to further enhance the utility of as-built BIM models, benefiting facility owners and managers.

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