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Cloud-based Building Information Modelling (CBIM): Software Engineers' Insights into Improving Asset Information Quality

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Abstract

Purpose: This research investigates the capabilities of CBIM in managing quality asset information, drawing upon software engineers' perspectives. Compelling statistics highlight the relationship between building information and environmental sustainability. However, despite the growing utilisation of CBIM in the Architecture, Engineering and Construction (AEC) industry, a significant knowledge gap remains concerning its effectiveness in maintaining quality asset information.

Design/methodology/approach: This study employed an exploratory qualitative approach, utilising semi-structured interviews with thirteen software engineers actively developing technological solutions for the AEC industry. Following thematic analysis, the findings are categorised into four dimensions: strengths, weaknesses, opportunities, and technological limitations. Subsequently, these findings are analysed in relation to previously identified information quality problems.

Findings: This research reveals that while CBIM improves project coordination and information accessibility, its effectiveness is challenged by the need for manual updates, vulnerability to human errors, and dependency on network services. Technological limitations, notably the absence of automated updates for as-built drawings and the risk of data loss during file conversions in the design phase, coupled with its reduced capability to validate context-specific information from the user's viewpoint, emphasise the urgent need for managerial strategies to maximise CBIM's capabilities in addressing information quality problems.

Originality/value: This study augments the understanding of CBIM, highlighting the managerial implications of a robust information management process to safeguard information integrity. This approach fosters sustainable practices anchored in reliable information essential for achieving desired outcomes. The findings also have broader managerial implications, especially for sectors that employ CBIM as an instrumental tool.

KEYWORDS: Cloud-based BIM, asset information quality, information quality, sustainable information management, built environment

1. Introduction

Buildings stand at the forefront of the global energy challenges. More than just structures, they significantly contribute to energy consumption and carbon emissions, representing 40% of global energy use and over 30% of worldwide CO_2 emissions, higher than the transportation and industrial sectors (Kiamili *et al.*, 2020; Roberts *et al.*, 2018; Santos *et al.*, 2019). The United States Department of Energy reports that approximately half of the energy used in buildings is for heating and cooling. Addressing this issue, the World Green Building Council has set ambitious targets: a 40% reduction in embodied and net-zero operational carbon by 2030, progressing to net-zero carbon for the entire lifecycle of buildings by 2050 (Roberts *et al.*, 2020; World Green Building Council, 2019). These goals are vital for building sustainable practices in the building industry, as the environmental impact of today's construction choices will have long-term consequences (Durdyev *et al.*, 2022).

In this context, quality asset information is integral to driving environmental sustainability practices. Originally gathered at the handover phase of a building construction project, this information provides essential asset information about the building (Pinheiro, 2019). Initially static, this information evolves dynamically in response to various projects throughout the building's lifecycle, requiring adequate information management to be effective (Leygonie, 2020). Accurately updated asset information is indispensable for maintenance and operational support while achieving the expected life of buildings (Chang *et al.*, 2022). This information is intricately linked to environmental sustainability activities in buildings. Martins *et al.* (2019) argue how asset information can mitigate environmental damage or, if managed inadequately, intensify it. For example, poorly maintained equipment consumes more energy and emits more harmful residues than well-maintained ones (Karpook and Meric, 2023). Given the complexity of building systems and elements, Yalcinkaya and Vishal Singh (2014) underscore the growing importance of dependable asset information as a key enabler for various environmental sustainability initiatives.

From an information management perspective, the growing adoption of Building Information Modelling (BIM) holds significant potential for augmenting the quality of asset information.

BIM excels during the project delivery phase by creating a compressive suite of essential asset details, spanning spatial zoning to individual components. Its capabilities include generating extensive non-graphical information, such as error-reducing spreadsheets, through various extensions and plugins (Pärn and Edwards, 2017). This wealth of information proves invaluable in the use phase, including energy monitoring and sustainability management (Wong *et al.*, 2018). BIM's advanced data storage and ability to produce reliable, in-depth information mark it as a key player in improving building operations. Matarneh *et al.* (2019a) highlight BIM's emerging role, underscoring its transformative impact on building management and maintenance, steering them toward enhancing sustainability.

BIM's ubiquitously quoted tangible benefits have recently been amplified by integrating cloud-computing technologies. These advancements have shifted traditional desktop solutions to the cloud, fostering greater collaboration and more efficient information flow during the design phase. Despite these tangible benefits, the quality of asset information continues to pose a persistent challenge, as Shalabi and Turkan (2017) noted. Moreover, manual data entry is necessary for many building information management systems due to the lack of automated information updates, leading to frequent human errors and omissions (Kumar and Lin, 2020). As CBIM becomes prevalent in the building sector, a notable knowledge gap emerges regarding its effectiveness in managing quality asset information during the use phase of buildings. This gap leads us to the central research question:

To what extent can CBIM ensure the quality of asset information during the use phase of buildings?

To address this research question, this study employs an exploratory approach to investigate CBIM's information management capabilities from the software engineer's viewpoint. This approach is unique yet important for uncovering the inherent technological limitation of CBIM and understanding how to utilise this technological solution to enhance the quality of information effectively. These insights are then cross-referenced with the existing information quality problems, providing a fresh perspective on CBIM's effectiveness in managing quality information. The results of this research enhance the current knowledge of CBIM and provide practical and actionable contributions beyond the building sector.

The study is structured as follows: Section 2 reviews the extant literature on cloud computing, BIM, CBIM and the concept of information quality. Section 3 outlines the methodology used to assess CBIM's capabilities in information management through the lens of software engineers. Section 4 presents the research findings. Section 5 discusses the key findings, theoretical contributions, practical implications, limitations of this study and future research directions based on the findings. Finally, Section 6 presents the conclusions drawn from this research.

2. Literature Review

2.1. Cloud-based Building Information Modelling (CBIM)

Digital transformation has become an invaluable process for improving the productivity of the AEC industry, which is highly fragmented and involves data-intensive processes across the supply chain and lifecycle (Singh, 2019). BIM represents the modelling techniques used to produce, communicate, analyse, and store information about buildings throughout their design, construction, and serviceable life. Specifically, through access to accurate object-oriented information at the correct time, BIM facilitates an integrated design and construction process, resulting in high-quality buildings at lower costs and reduced project duration. It also supports improved facility management (FM) and future refurbishment of buildings (Sacks *et al.*, 2018). Serving as a shared knowledge source and storage, BIM can reduce the need for redundant data collection and reformatting, leading to more efficient data storage and information exchange and reduced costs associated with the lack of interoperability, automation of checking and analysis, etc.

BIM enables modern construction projects to be complex and complicated, requiring collaboration among various subcontractors for seamless data sharing throughout a project's lifecycle (Alreshidi *et al.*, 2016; Ghaffarianhoseini *et al.*, 2017). Traditionally, desktop-based BIM has faced challenges in maintaining model consistency and integrity, hindered by coordination demands, interoperability issues among different software tools, and difficulties in handling ongoing modifications and manual changes (Sacks *et al.*, 2022). Cloud computing emerges as a solution, enabling on-demand delivery of configurable computing resources over the Internet. This transition from desktop to server-based processing enhances the utilisation of limited resources like computing power and storage. Integrating BIM with cloud computing fosters efficient, cross-domain collaboration, ensuring a unified and consistent BIM model. Additionally, it reduces the operational and maintenance costs of computing infrastructure. As indicated by Zhao and Taib (2022) and other studies, CBIM will become the predominant method, leveraging cloud computing's advantages. This evolution in BIM application promises enhanced collaboration and efficiency in complex construction projects and safeguards the quality of asset information.

Compared with conventional BIM, CBIM offers opportunities for improving cross-domain and cross-organisation data storage, information exchange, and remote access, supporting collaboration among multiple parties. Afsari *et al.* (2016) categorise three classifications of data flow architectures used to enable the CBIM:

1. Manual transfer: This involves the labour-intensive transfer of vendor-neutral file-based BIM (e.g., Industry Foundation Classes (IFC), IFC in short), which, despite being cumbersome, is the most prevalent method for information exchange.
2. BIM server technology: This approach uses a single-source data server for data sharing among project partners. Its limitation is the centralisation of BIM files on one server, leading to potential bottlenecks and scalability issues.
3. Data interchange hub: this technology automates data flow between applications through a hub, which synchronises data changes from different participants.

Various companies and academic institutions have developed CBIM solutions, such as Autodesk BIM360, Trimble Connect, BIMserver, and Bentley i-Model (Wong *et al.*, 2014).

Table 1 shows the recent CBIM literature, highlighting their purpose, adopted BIM format, data transmission process, and the addressed information quality problems. BIM data can be represented, stored, and exchanged in different formats in collaborative BIM-based processes. The IFC standard, a neutral data format, enhances BIM interoperability across platforms. Model View Definitions (MVDs) also facilitate specific data exchange requirements between platforms. An alternative approach utilises semantic web technology for representing building information, such as spaces, assets, and construction processes. This approach offers flexibility in representing and combining data from different domains into computer-readable graphs, enabling efficient federation. In cloud-based data transmission, several protocols are used for effective Internet exchange. These include the basic Transmission Control Protocol/Internet Protocol (TCP/IP), Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP). These protocols support a range of data formats, from complete IFC models to specific IFC MVDs or BIM sub-graphs, varying in data size based on the application, software, and intended use cases. The application perspective includes examining CBIM technologies that facilitate collaboration, practices encouraging or hindering team collaboration, and data governance strategies for secure and efficient data usage (Mutis and Mehraj, 2022).

Table 1. The applications of CBIM and the addressed information quality problems.

2.2. Information Quality

While BIM, whether desktop-based or cloud-enabled, has been proven as an efficient and collaborative method for managing and storing information in project delivery and the use phase, it is important to note that the technology itself does not automatically assure the quality of the embedded information (Pärn *et al.*, 2016). Since essential building information predominately originates from construction projects, the effective realisation of sustainability objectives through BIM hinges critically on the quality of information fed into the system (Pinheiro, 2019). Subsequently, the management of this information across the entire lifecycle of the physical assets plays a pivotal role in ensuring the success of these sustainability goals.

Information quality is a complex and multi-dimensional concept without a universally accepted set of dimensions and related definitions of each dimension (Wand and Wang, 1996; Woodall *et al.*, 2013). The quality of information is assessed based on its ability to consistently meet user expectations and requirements (e.g., sustainability), a subjective measure that varies by context (Pringle *et al.*, 2002; Strong *et al.*, 1997; Wang and Strong, 1996). Effective information management addresses this through the entire information lifecycle, including its creation, organisation, storage, distribution, and use (DAMA International, 2017). Commonly cited dimensions in literature are accuracy, completeness, consistency, and timeliness (Chang *et al.*, 2022; Woodall *et al.*, 2013):

- Accuracy: Information reflects the actual value.
- Completeness: All required information is present to meet the user's requirements.
- Consistency: The absence of difference when comparing multiple information.
- Timeliness: Information is sufficiently current for the task at hand.

Further elaborating on information quality problems, Ge and Helfert (2007), drawing from previous studies, classified information quality issues into two categories: (1) context-independent and context-dependent. Context-independent problems are those that occur irrespective of the specific situation or application, including issues like spelling errors, data omission, duplications, inconsistent formats, and incorrect values (Eppler, 2006; Oliveira *et al.*, 2005). Conversely, context-dependent problems are those that arise in response to specific situational or contextual factors, with violation of company and government regulations serving as a prime example (Pipino *et al.*, 2002). Additionally, the same authors evaluated these issues from two distinctive lenses: the user perspective, which focuses on problems identified by information consumers, and the data perspective, which addresses issues that are inherent to the data itself, independent of any specific user's viewpoint (See Table 2).

Table 2. Categorisation of information quality problems

Leveraging the information quality problems listed in Table 2, this study explores CBIM's contributions to preventing quality deterioration and ensuring the quality of asset information.

3. Methodology

This research argues that inductive theory generation on CBIM capabilities requires an in-depth understanding of CBIM's inherent limitations through those who help develop this tool. Therefore, this research employed a mono-method qualitative approach, leveraging semi-structured interviews with software engineers. A sample of software engineers proficient in developing technological solutions for the AEC industry was selected. This deliberate choice facilitated an in-depth analysis of their unique viewpoints, providing technological capabilities and efficiency of CBIM in handling quality asset information.

3.1. Sampling and recruitment

Using the purposive sampling technique described by (Lucas, 2014), this study engaged 13 participants from software solution providers in the US, UK, Finland and Germany. To ensure that the sample represents the population, potential participants were required to develop technological solutions for the AEC industry, with a specific focus on cloud technology. Table 3 details the profiles of the participants engaged in the interviews.

3.2. Data collection

Semi-structured interviews were chosen as the primary data collection method. Interviews were more valuable than the survey in meeting the aim of this study because they allowed participants to share experiences on the subject under investigation. Before the interviews, the questions were systematically categorised into three main groups: (1) the advantages of leveraging CBIM for effective information management, (2) the prevalent technological barriers faced by CBIM, and (3) the ramifications of employing CBIM in the domain of asset information management. Questions about the advantages of CBIM were instrumental in illuminating its strengths and potential openings for innovation and improvement. Subsequently, questions addressing technological challenges revealed the limitations intrinsic to CBIM, especially concerning managing diverse asset information predominately rooted in current technological constraints.

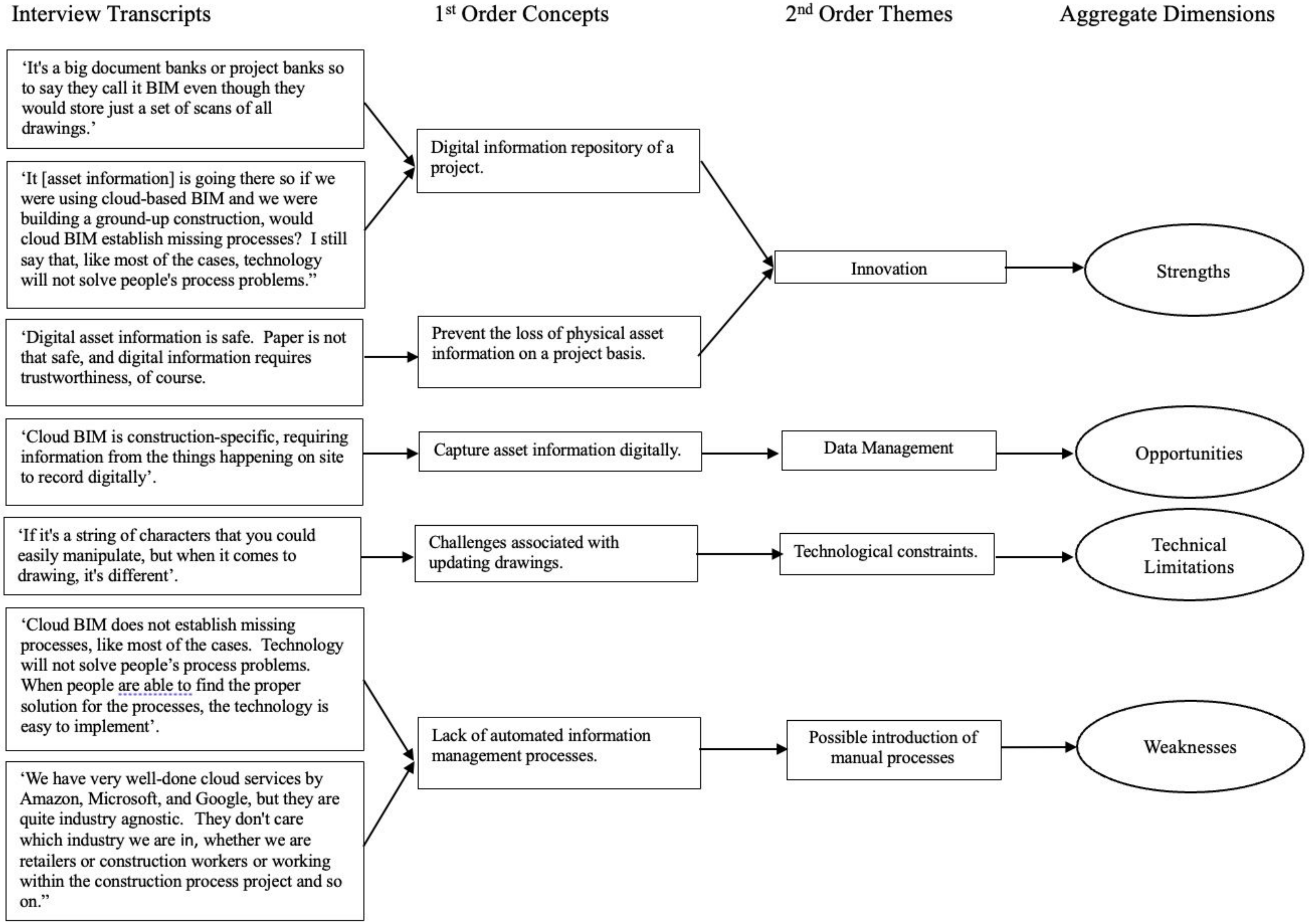
Table 3. List of participants

Participants had the option to skip questions deemed irrelevant or sensitive, particularly those proving current product development specifics. Interviewing continued until data saturation was reached, meaning no new information emerged from participants, as Easterby-Smith *et al.* (2021) suggested. Interviews averaged 60 minutes. With prior consent, all interviews were recorded and later transcribed for detailed analysis.

3.3. Data analysis

The data analysis followed the steps of thematic analysis recommended by Gioia *et al.* (2013). Firstly, the interviews were coded using NVivo, a qualitative analysis software, augmented by extensive notetaking to transform the raw data into 69 preliminary concepts. Each researcher performed independent coding of the interviews reflecting the terminology used by participants. Next, the researchers refined the coding scheme. Subsequently, the study performed a data reduction process, eliminating redundant concepts, discarding categories irrelevant to the research question, and merging categories into 16 second-order themes (Gioia *et al.*, 2013; Grodal *et al.*, 2021). The final cycle culminated in consolidating these themes into 4 broader dimensions: strengths, weaknesses, opportunities, and technical limitations.

To demonstrate the data analysis process, Figure 1 provides an example from an interview, illustrating the steps involved in processing interview data. Initially considered raw data, the interview transcript undergoes categorisation into ‘first-order concept’, which emerges as 69 categories from an analysis of 13 interviews. These first-order concepts are further refined into ‘second-order themes’, such as ‘Innovation’, ‘Data Management’ and ‘Technology Constraints’, totalling 16 themes. These second-order themes are then evaluated to identify ‘Strengths’, ‘Weaknesses’, ‘Opportunities’, and ‘Technological Limitations’.



'It's a big document banks or project banks so to say they call it BIM even though they would store just a set of scans of all drawings.'

'It [asset information] is going there so if we were using cloud-based BIM and we were building a ground-up construction, would cloud BIM establish missing processes? I still say that, like most of the cases, technology will not solve people's process problems."

'Digital asset information is safe. Paper is not that safe, and digital information requires trustworthiness, of course.

'Cloud BIM is construction-specific, requiring information from the things happening on site to record digitally'.

'If it's a string of characters that you could easily manipulate, but when it comes to drawing, it's different'.

'Cloud BIM does not establish missing processes, like most of the cases. Technology will not solve people's process problems. When people are able to find the proper solution for the processes, the technology is easy to implement'.

'We have very well-done cloud services by Amazon, Microsoft, and Google, but they are quite industry agnostic. They don't care which industry we are in, whether we are retailers or construction workers or working within the construction process project and so on."

Figure 1. An example of thematic analysis of an interview

Significant insights were distilled from the raw data, transitioning software engineers' feedback into an interpretive analysis that enriches understanding of CBIM's ability to manage quality asset information.

4. Results

This section presents CBIM's capabilities in managing quality asset information from the perspective of software engineers. Findings are derived from thematic analysis of interviews with anonymous coding (e.g., RQ3P1 and RQ3P2) to maintain confidentiality.

Adopting a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, findings are categorised into Strengths, Weaknesses, Opportunities, and Technological Limitations, with 'Threats' adapted to 'Technological Limitations' to better align with the focus of this study. Figure 2 illustrates the findings. Further, linking these findings with the information quality problems identified by Ge and Helfert (2007) are displayed in Figure 3.

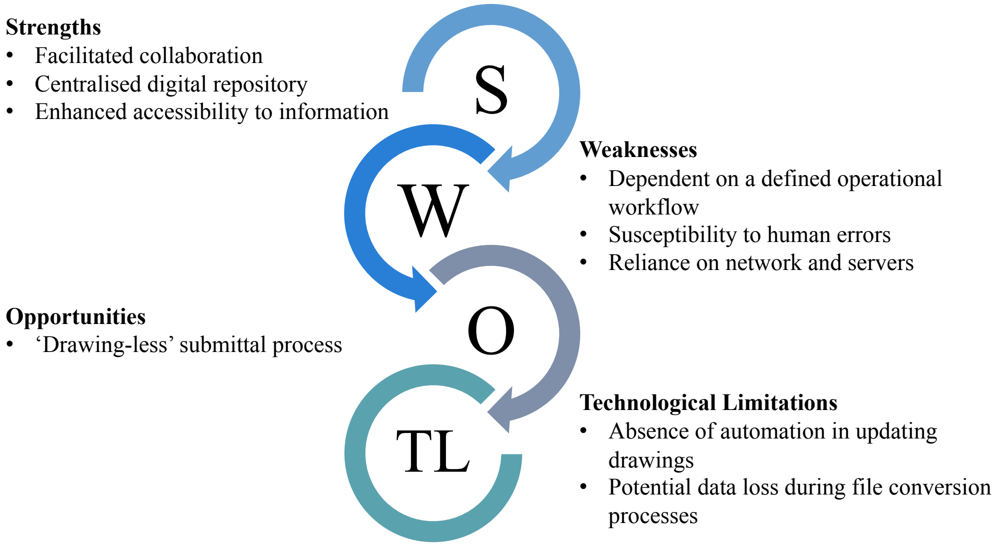


Figure 2. The capabilities of CBIM from software engineers' viewpoint

4.1. Strengths

The participants have identified three compelling strengths of CBIM, underscoring its vital role in enhancing asset information quality within the building sector: (1) enhanced collaborative design phase, (2) robust digital storage, and (3) accessibility.

The participants indicate that CBIM enhances *'collaboration during the design phase*', leading to generating quality design in construction projects (RQ3P1). As RQ3P12 elucidated, *'CBIM can orchestrate the multi-faceted information among the diverse project elements.'* The collaboration among project participants streamlines workflows, while fostering cross-domain collaboration to allow 'each *[design element]* is *uniquely identified, and its details are accurately represented in consistent manners'* (RQ3P3). This collaborative approach fosters the systematic representation of asset information, tailoring the uniqueness of each asset while distinctly expressing design details coherently (Liu *et al.*, 2020; Sacks *et al.*, 2022).

Another notable strength of CBIM as its innate ability for digital information storage, which integrates '*naturally in the cloud-based environments'* (RQ3P4). In this context, CBIM adeptly provides *'a single source of information containing multiple layers of mechanical, electrical, and architectural information*' in contrast to traditional compilations of information (RQ3P1). This system, acting as a robust repository for asset information, RQ3P2 underscored accessibility offered by CBIM, stating, '*Cloud-based BIM enables us to find a vast amount of information while providing easy access to those needs' information.* Moreover, *'When a new employee is onboard, one can just sort through the CBIM to find the necessary information' (RQ3P2)*. Further, utilising CBIM as a centralised repository can reduce the risk associated with the loss of tangible information, such as drawings.

4.2. Weaknesses

CBIM offers considerable benefits, yet it simultaneously introduces a set of challenges. Participants have pinpointed key weaknesses: (1) an inability to define information management processes, (2) human errors due to the reliance on manual processes, and (3) the dependency of networks and servers. These shortcomings highlight managerial implications within the domain of CBIM.

Although adopting technological solutions can enhance efficiency when using them appropriately, they do not inherently establish an associated *'workflow*' (RQ3P7). Effective workflows are the structural pillars of any organised process, vital for executing tasks efficiently and uniformly. RQ3P2 notes that *'I feel strongly that technological solutions [software] do not define the workflows.'* Without well-defined workflows, asset information management via CBIM might not reach its full potential (RQ3P2). The lack of a methodical approach heightens the risk of introducing errors and operational inefficiencies, undercutting the potential benefits of the technology (RQ3P7). Consequently, while CBIM presents an opportunity to advance operational efficiency, it is incumbent upon organisations to devise and implement bespoke, robust workflows designed to align with and amplify the strengths of CBIM. As a result, software engineers asserted the need for a robust *'internal information management procedure'* to prevent the risk of information quality deterioration (RQ3P3, RQ3P5, RQ3P8, RQ3P11, & RQ3P13).

Additionally, CBIM's reliance on manual updates jeopardises asset information quality. As RQ3P7 indicates, *'All design elements are manually created during the design phase. Consequently, the quality of these design elements is directly proportional to the designers' expertise and attention to detail.'* Even during the use phase, CBIM depends on manual updates of existing asset information corresponding to various building projects, which are prone to *'human errors and oversights'* due to the lack of automated information update processes (RQ3P3). This deficiency is especially pronounced in the upkeep of as-built drawings, which are essential for accurate building representations as they guide various activities, including maintenance, renovations, and physical space management. Continuous quality assurance measures among project participants are necessary, requiring designers involved in each building project to approve the quality of handover information before it is updated.

Finally, the dependency on networks and servers is recognised as an additional weakness of CBIM. Continuous network connectivity emerges as a foundation for CBIM efficacy, where disruptions can cripple system functionality, a situation that is particularly acute in regions with inconsistent internet services (RQ3P8 and RQ3P10). Server dependency further compounds this risk. Server outages can result in a complete loss of access to vital asset information, leading to halted workflows and asset management activities. RQ3P12 also notes the critical risk of information loss stemming from server crashes. These dependencies introduce substantial risks of operational delays and inefficiencies. As such, there's a pressing need for CBIM to develop resilient data management capabilities, including *'implementing redundant system'*, *'crafting offline functionality'* or *'exploring decentralised data storage solutions'* (RQ3P6, RQ3P7 and RQ3P13).

4.3 Opportunities

RQ3P4, RQ3P9, and RQ3P10 collectively highlighted the transformative opportunity in facilitating a 'drawing-less process' in the submittal procedures. The traditional submittal process, characterised by a sequential approval mechanism required prior to fabrication commencement, is undergoing transformative changes. ‘*For example, the contractor can submit structural details, such as the I-beam and associated connector details, directly through CBIM for the structural engineer’s approval without generating hard copies of submittal drawings and the associated material specifications. ‘The accessibility of 3D models on laptops and tablets has revolutionised the submittal process’, as articulated by RQ3P4.* Additionally, once submittals receive approval, they are readily available in an electronic format for fabrication purposes. RQ3P10 further stated that ‘*this shift towards a drawing-less [object-based] process is substantiated for national highway projects in the Nordic countries’*. This exemplifies the opportunities and efficiencies offered by digital submittal processes in the building industry facilitated by CBIM. It markedly reduces potential issues related to information quality and guarantees the effective distribution of information across stakeholders.

4.4. Technological Limitations

Despite CBIM’s innovative opportunities, software engineers pointed out technological constraints in managing asset information quality: (1) a lack of an automated process of updating as-built drawings and (2) information loss during the file conversion.

RQ3P1 elucidated, ' *The concept of CBIM is using BIM software on cloud services, without appropriate automated information flow processes.* If *it is a string of characters [non-graphical information], you could easily manipulate to update the information using Excel, but when it comes to drawings, it is different’. We currently do not have an automated process for updating as-built drawings to reflect onsite modifications.’* To illustrate this point, non-graphical information, such as the models, makers, and serial numbers of installed building components, can be extracted into a tabular format, such as an Excel spreadsheet, to facilitate transferring purposes. However, any modifications to the current as-built drawings require updates within the original file format, such as a Revit model. Countering this perspective, RQ3P9 presents the *‘point cloud scanning technique’*. However, this method encounters limitations, including extensive data processing time, scalability, and its restriction to capturing spatial information, omitting essential details in enclosed areas, such as pipes behind walls or above ceilings.

In addition, RQ3P6 elaborated on inherent problems of information loss due to technological constraints. This problem is exemplified in the process of ‘*converting a 3-dimensional model to a 2-dimensional plan, where the conversion fails to transfer the embedded information within the* *objects to the plan',* underscoring a significant challenge posed by technological constraints. Typically, a 3D model is converted into 2D plans in AutoCAD format, which are widely utilised for construction and space utilisation purposes. However, it is crucial to understand that while dimensional modifications and configurational updates of 2D plans in AutoCAD format may capture spatial alterations, they do not synchronise updates related to essential attributes, such as wall types and thickness, in the corresponding 3D model. Delving this issue with a technical lens, RQ3P3 illustrated a prevalent information issue of information loss through practical applications: *'Using IFC, for example, we first map data from source X to IFC Y, and then when reading data from IFC to application Z, we do another conversion. There are two opportunities for information loss. Even if the information could be presented both in X and Z but not in the intermediary format Y, the information is lost even though a direct link between X and Z could perform the mapping'.* This explanation highlights the challenge of maintaining coherent and up-to-date asset information across different model formats.

4.5. CBIM's capabilities to address information quality problems

This section provides an analysis of CBIM's effectiveness in addressing the quality issues identified by Ge and Helfert (2007), as depicted in Figure 3. The analysis suggests that CBIM is proficient in correcting context-independent data issues such as spelling and syntax errors. Yet, its effectiveness is less assured when it comes to complex problems like the absence of necessary data or incorrect values, indicating a need for improving data validation functions. From the user's standpoint, CBIM is effective in providing access, retrieval, and secure storage of information, facilitating fundamental user interactions. Nevertheless, it struggles with transforming data into more user-friendly formats without compromising data integrity, reflecting a crucial area for enhancement. These observations signal that while CBIM competently addresses certain information quality issues, it requires further refinement to meet the demands of context-independent information management and user experience.

Conversely, Figure 3 reveals that there were no specific information quality issues directly attributable to CBIM from the context-dependent data perspective. However, it becomes evident that CBIM is limited to resolving information quality problems to meet specific situations or user requirements. This shortfall calls attention to the need to optimise resource distribution, analyse business challenges, re-engineer processes, and re-align information flow from sources to address problems effectively (Ge and Helfert, 2007).

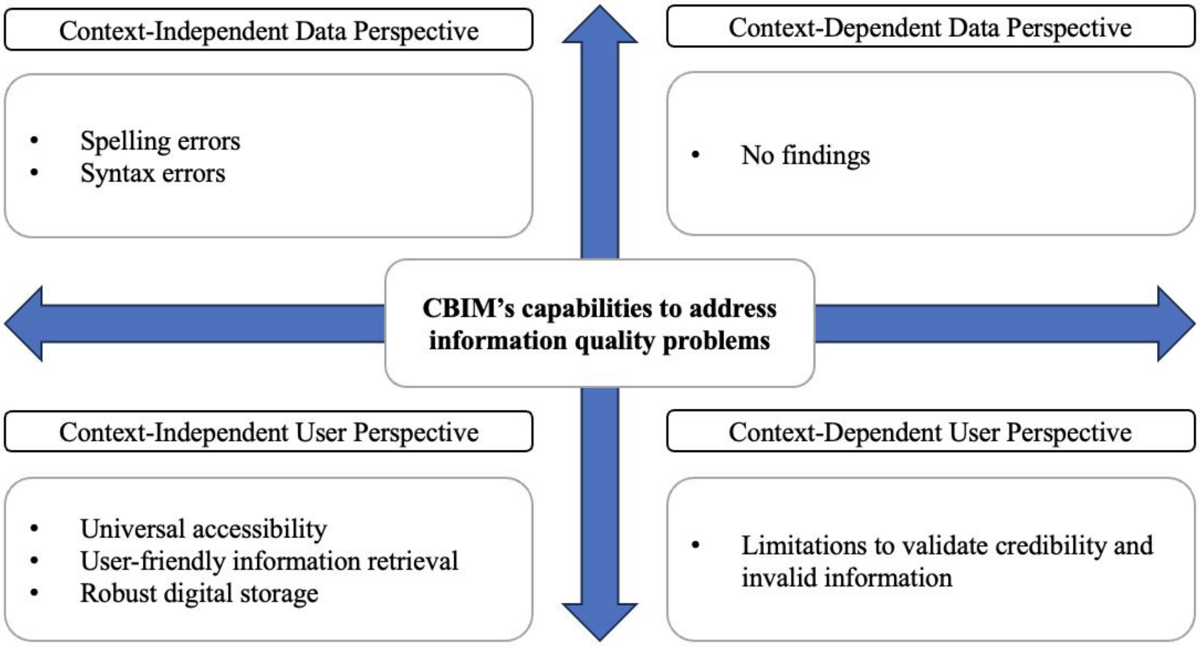


Figure 3. A summary of CBIM's capabilities in asset information management

The SWOT analysis reveals various dimensions of CBIM's capabilities while highlighting its ability to validate context-dependent user perspective issues requires managerial oversight.

5. Discussion

This research has elucidated CBIM's capabilities in addressing information quality problems through the lens of software engineers developing technological solutions for the AEC industry. Understanding the intrinsic technological limitations is vital for optimising its potential in information management. Building on these insights, this section discusses contributions to theory and practice, acknowledges methodological limitations and provides suggestions for future studies.

5.1. Theoretical contribution

The theoretical contribution of this research lies in its deep exploration of the dynamic interplay between CBIM and asset information management, specifically addressing the complex challenges faced in preventing factors leading to the deterioration of handover information quality. This research acknowledges the capabilities of CBIM in enhancing collaborative design practices, a point underpinned by the findings of Sacks *et al.* (2022), yet it goes further to identify and theorise on the operational challenges, particularly the risk of information loss during the design phase due to data conversion across disparate BIM software formats (Sacks *et al.*, 2018). These operational challenges are not merely technical issues; they reflect deeper systemic issues faced in the AEC industry, as argued by (Singh, 2019). For example, when multiple BIM applications are involved, the incompatibility between data structures can lead to significant information deterioration. This is not just a technological limitation of CBIM; it also poses a substantial risk to the reliability of handover information, which is critical for the operational integrity of physical assets (Matarneh *et al.*, 2022).

As such, this research proposes an 'Integration Theory of CBIM and Asset Information Management', which advocates for a lifecycle-oriented approach to information quality. This approach recognises the necessity of integrating CBIM practices within a broader asset management strategy to align with the quality expectations of information users (Ge and Helfert, 2007). It advocates for context-specific processes that integrate CBIM, enabling automated quality control mechanisms that utilise advanced analytics, machine learning, and artificial intelligence to not only reactively identify but also proactively predict and mitigate potential deterioration in information quality (Zabin *et al.*, 2022; Zhang, 2020). Moreover, the theory introduces the concept of adaptive learning systems embedded within CBIM, which are designed to refine information management practices by learning and evolving based on ongoing feedback and information. This adaptability is crucial in a field characterised by constant change and evolution, where asset information must be as dynamic and responsive as the environments in which it is applied.

By proposing this theory, the research seeks to broaden the existing theoretical landscape of asset information management to include elements specific to CBIM, such as the capacity for real-time updates, the cultivation of collaborative environments beyond the design phase, and the strategic use of digital twins to optimise the management of physical assets. The theory positions CBIM not as a mere repository or static tool but as a dynamic facilitator of asset management, potentially bringing about significant enhancements in the efficiency of asset management, sustainability, and adaptability. In envisioning a holistic integration of CBIM within asset management, this research sets forth a theoretical framework that aims to provoke a paradigm shift toward more efficient and sustainable practices in the built environment. This paradigm shift requires overcoming significant challenges, including ensuring interoperability across diverse BIM tools, developing predictive analytics for quality control, and fostering an industry-wide acceptance of these advanced methodologies.

5.2. Practical relevance

Grounded in the 'Integration Theory of CBIM and Asset Information Management', this theory advocates for a lifecycle-centric approach underpinned by continuous adaptation and feedback mechanisms. These mechanisms are essential for enhancing asset information quality through CBIM. A practical application of this theory is developing an advanced collaborative platform designed to support CBIM activities. From the perspective of technological solution providers, this innovation facilitates using cloud-based storage to support multiple products from the same company, eliminating the need to transfer project data from one solution to another. Such an approach reduces errors caused by human intervention and the potential loss of information during the file import and export processes. Simultaneously, this model enables end-users to leverage analytics for various asset management activities, fostering informed decision-making underpinned by quality asset information. This paradigm shift propels asset management from traditional, static practices to dynamic, feedback-driven processes that are emblematic of adaptive learning principles.

Moreover, managing as-built drawings can benefit from incorporating automated quality control mechanisms that resonate with the proposed theoretical insights. Innovations such as CBIM plugins utilising emerging scanning techniques to automate updates to as-built drawings are pivotal. They can mirror real-time modifications, aiming to minimise manual processing for drawing updates, reduce human errors, and ensure the quality of as-built drawings.

Further, overcoming challenges related to internet connectivity, especially in less developed or rural areas, involves harnessing the capabilities of digital twin technologies. This approach is bolstered by advancements in 5G technology and the anticipation of 6G networks. It aligns with the theory's advocacy for real-time updates and collaborative environments, illustrating the practical application of theoretical concepts into tangible, actionable strategies. Integrating digital twins with CBIM optimises the asset management process, rendering it more efficient, sustainable, and adaptable to the evolving dynamics of the built environment.

Embedding these practical recommendations presents a visionary strategy for employing CBIM in asset management. It illustrates how theoretical insights can catalyse significant practice transformation, establishing a new standard for efficiency, sustainability, and adaptability in the built environment. Beyond the AEC industry, sectors such as civil engineering, infrastructure, transportation, aviation, manufacturing, real estate, urban planning, and smart city initiatives stand to benefit from these recommendations. Implementing these recommendations promotes an environment where the potential of CBIM can be fully realised, facilitating various activities with quality asset information.

5.3. Limitations and suggestions for future research

The exploration of CBIM in the AEC industry, primarily from software engineers' perspectives, presents vital insights into its capabilities and limitations within asset information management. However, this concentration limits the exploration to a singular viewpoint, potentially missing the broader spectrum of challenges and opportunities perceived by the end users, such as asset management professionals. While rich in detail, this research's qualitative nature constrains the conclusions' scalability and generalisability. Notably, the technical hurdles highlighted, including information loss during file conversions and the absence of automated updates for as-built drawings, underscore the need for technological advancements and highlight the complexity of implementing CBIM in real-world scenarios.

Future research into CBIM must broaden to include diverse stakeholder perspectives, including end-users and regulatory bodies, enhancing insights into CBIM's utility during the use phase of buildings. Integrating quantitative methodologies, such as surveys and case studies, will complement existing qualitative insights, offering a detailed view of the effects of CBIM on asset information quality and operational efficiency. Addressing technological advancement is critical, focusing on developing algorithms and machine learning techniques for automating information updates and minimising information loss during file conversions. This technological push should be accompanied by efforts to enhance software interoperability, ensuring consistent information quality throughout the asset's lifecycle. Moreover, constructing comprehensive frameworks for CBIM implementation and conducting longitudinal studies will be vital. This framework should incorporate best practices for information management and stakeholder collaboration, while longitudinal studies could reveal CBIM's long-term sustainability and economic benefits, providing a holistic view of its potential enhancement and efficiency.

6. Conclusions

This study critically evaluated the application of CBIM in the building sector, focusing on its capabilities in managing information quality, as perceived by software engineers. Key findings of this research indicate that while CBIM can address context-independent quality problems such as spelling errors and digital storage, it requires additional managerial oversights and strategic operational adjustments to exploit its potential fully. A comparative review of these findings with existing literature reveals that although adopting CBIM is widespread in the AEC industry, the focus largely remains on technological advancements rather than on its integration into broader information management processes, a discrepancy that highlights a significant area for future research. This study extends the current understanding of CBIM's capabilities by highlighting the necessity for continuous quality assurance and adopting advanced technological strategies to overcome CBIM's limitations. Moreover, it emphasises the importance of refining CBIM integration strategies and procedural optimisations to address these challenges effectively. Therefore, strategic management and continuous improvement are crucial to address its operational vulnerabilities and maximise its capabilities to improve handover information quality.

7. Acknowledgement

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Cloud-based Building Information Modelling (CBIM): Software Engineers' Insights into Improving Asset Information Quality

Abstract

Purpose: This research investigates the capabilities of CBIM in managing quality asset information, drawing upon software engineers' perspectives. Compelling statistics highlight the relationship between building information and environmental sustainability. However, despite the growing utilisation of CBIM in the Architecture, Engineering and Construction (AEC) industry, a significant knowledge gap remains concerning its effectiveness in maintaining quality asset information.

Design/methodology/approach: This study employed an exploratory qualitative approach, utilising semi-structured interviews with thirteen software engineers actively developing technological solutions for the AEC industry. Following thematic analysis, the findings are categorised into four dimensions: strengths, weaknesses, opportunities, and technological limitations. Subsequently, these findings are analysed in relation to previously identified information quality problems.

Findings: This research reveals that while CBIM improves project coordination and information accessibility, its effectiveness is challenged by the need for manual updates, vulnerability to human errors, and dependency on network services. Technological limitations, notably the absence of automated updates for as-built drawings and the risk of data loss during file conversions in the design phase, coupled with its reduced capability to validate context-specific information from the user's viewpoint, emphasise the urgent need for managerial strategies to maximise CBIM's capabilities in addressing information quality problems.

Originality/value: This study augments the understanding of CBIM, highlighting the managerial implications of a robust information management process to safeguard information integrity. This approach fosters sustainable practices anchored in reliable information essential for achieving desired outcomes. The findings also have broader managerial implications, especially for sectors that employ CBIM as an instrumental tool.

KEYWORDS: Cloud-based BIM, asset information quality, information quality, sustainable information management, built environment

1. Introduction

Buildings stand at the forefront of the global energy challenges. More than just structures, they significantly contribute to energy consumption and carbon emissions, representing 40% of global energy use and over 30% of worldwide CO_2 emissions, higher than the transportation and industrial sectors (Kiamili *et al.*, 2020; Roberts *et al.*, 2018; Santos *et al.*, 2019). The United States Department of Energy reports that approximately half of the energy used in buildings is for heating and cooling. Addressing this issue, the World Green Building Council has set ambitious targets: a 40% reduction in embodied and net-zero operational carbon by 2030, progressing to net-zero carbon for the entire lifecycle of buildings by 2050 (Roberts *et al.*, 2020; World Green Building Council, 2019). These goals are vital for building sustainable practices in the building industry, as the environmental impact of today's construction choices will have long-term consequences (Durdyev *et al.*, 2022).

In this context, quality asset information is integral to driving environmental sustainability practices. Originally gathered at the handover phase of a building construction project, this information provides essential asset information about the building (Pinheiro, 2019). Initially static, this information evolves dynamically in response to various projects throughout the building's lifecycle, requiring adequate information management to be effective (Leygonie, 2020). Accurately updated asset information is indispensable for maintenance and operational support while achieving the expected life of buildings (Chang *et al.*, 2022). This information is intricately linked to environmental sustainability activities in buildings. Martins *et al.* (2019) argue how asset information can mitigate environmental damage or, if managed inadequately, intensify it. For example, poorly maintained equipment consumes more energy and emits more harmful residues than well-maintained ones (Karpook and Meric, 2023). Given the complexity of building systems and elements, Yalcinkaya and Vishal Singh (2014) underscore the growing importance of dependable asset information as a key enabler for various environmental sustainability initiatives.

From an information management perspective, the growing adoption of Building Information Modelling (BIM) holds significant potential for augmenting the quality of asset information.

BIM excels during the project delivery phase by creating a compressive suite of essential asset details, spanning spatial zoning to individual components. Its capabilities include generating extensive non-graphical information, such as error-reducing spreadsheets, through various extensions and plugins (Pärn and Edwards, 2017). This wealth of information proves invaluable in the use phase, including energy monitoring and sustainability management (Wong *et al.*, 2018). BIM’s advanced data storage and ability to produce reliable, in-depth information mark it as a key player in improving building operations. Matarneh *et al.* (2019a) highlight BIM’s emerging role, underscoring its transformative impact on building management and maintenance, steering them toward enhancing sustainability.

BIM's ubiquitously quoted tangible benefits have recently been amplified by integrating cloud-computing technologies. These advancements have shifted traditional desktop solutions to the cloud, fostering greater collaboration and more efficient information flow during the design phase. Despite these tangible benefits, the quality of asset information continues to pose a persistent challenge, as Shalabi and Turkan (2017) noted. Moreover, manual data entry is necessary for many building information management systems due to the lack of automated information updates, leading to frequent human errors and omissions (Kumar and Lin, 2020). As CBIM becomes prevalent in the building sector, a notable knowledge gap emerges regarding its effectiveness in managing quality asset information during the use phase of buildings. This gap leads us to the central research question:

To what extent can CBIM ensure the quality of asset information during the use phase of buildings?

To address this research question, this study employs an exploratory approach to investigate CBIM’s information management capabilities from the software engineer’s viewpoint. This approach is unique yet important for uncovering the inherent technological limitation of CBIM and understanding how to utilise this technological solution to enhance the quality of information effectively. These insights are then cross-referenced with the existing information quality problems, providing a fresh perspective on CBIM’s effectiveness in managing quality information. The results of this research enhance the current knowledge of CBIM and provide practical and actionable contributions beyond the building sector.

The study is structured as follows: Section 2 reviews the extant literature on cloud computing, BIM, CBIM and the concept of information quality. Section 3 outlines the methodology used to assess CBIM's capabilities in information management through the lens of software engineers. Section 4 presents the research findings. Section 5 discusses the key findings, theoretical contributions, practical implications, limitations of this study and future research directions based on the findings. Finally, Section 6 presents the conclusions drawn from this research.

2. Literature Review

2.1. Cloud-based Building Information Modelling (CBIM)

Digital transformation has become an invaluable process for improving the productivity of the AEC industry, which is highly fragmented and involves data-intensive processes across the supply chain and lifecycle (Singh, 2019). BIM represents the modelling techniques used to produce, communicate, analyse, and store information about buildings throughout their design, construction, and serviceable life. Specifically, through access to accurate object-oriented information at the correct time, BIM facilitates an integrated design and construction process, resulting in high-quality buildings at lower costs and reduced project duration. It also supports improved facility management (FM) and future refurbishment of buildings (Sacks *et al.*, 2018). Serving as a shared knowledge source and storage, BIM can reduce the need for redundant data collection and reformatting, leading to more efficient data storage and information exchange and reduced costs associated with the lack of interoperability, automation of checking and analysis, etc.

BIM enables modern construction projects to be complex and complicated, requiring collaboration among various subcontractors for seamless data sharing throughout a project's lifecycle (Alreshidi *et al.*, 2016; Ghaffarianhoseini *et al.*, 2017). Traditionally, desktop-based BIM has faced challenges in maintaining model consistency and integrity, hindered by coordination demands, interoperability issues among different software tools, and difficulties in handling ongoing modifications and manual changes (Sacks *et al.*, 2022). Cloud computing emerges as a solution, enabling on-demand delivery of configurable computing resources over the Internet. This transition from desktop to server-based processing enhances the utilisation of limited resources like computing power and storage. Integrating BIM with cloud computing fosters efficient, cross-domain collaboration, ensuring a unified and consistent BIM model. Additionally, it reduces the operational and maintenance costs of computing infrastructure. As indicated by Zhao and Taib (2022) and other studies, CBIM will become the predominant method, leveraging cloud computing's advantages. This evolution in BIM application promises enhanced collaboration and efficiency in complex construction projects and safeguards the quality of asset information.

Compared with conventional BIM, CBIM offers opportunities for improving cross-domain and cross-organisation data storage, information exchange, and remote access, supporting collaboration among multiple parties. Afsari *et al.* (2016) categorise three classifications of data flow architectures used to enable the CBIM:

1. Manual transfer: This involves the labour-intensive transfer of vendor-neutral file-based BIM (e.g., Industry Foundation Classes (IFC), IFC in short), which, despite being cumbersome, is the most prevalent method for information exchange.
2. BIM server technology: This approach uses a single-source data server for data sharing among project partners. Its limitation is the centralisation of BIM files on one server, leading to potential bottlenecks and scalability issues.
3. Data interchange hub: this technology automates data flow between applications through a hub, which synchronises data changes from different participants.

Various companies and academic institutions have developed CBIM solutions, such as Autodesk BIM360, Trimble Connect, BIMserver, and Bentley i-Model (Wong *et al.*, 2014).

Table 1 shows the recent CBIM literature, highlighting their purpose, adopted BIM format, data transmission process, and the addressed information quality problems. BIM data can be represented, stored, and exchanged in different formats in collaborative BIM-based processes. The IFC standard, a neutral data format, enhances BIM interoperability across platforms. Model View Definitions (MVDs) also facilitate specific data exchange requirements between platforms. An alternative approach utilises semantic web technology for representing building information, such as spaces, assets, and construction processes. This approach offers flexibility in representing and combining data from different domains into computer-readable graphs, enabling efficient federation. In cloud-based data transmission, several protocols are used for effective Internet exchange. These include the basic Transmission Control Protocol/Internet Protocol (TCP/IP), Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP). These protocols support a range of data formats, from complete IFC models to specific IFC MVDs or BIM sub-graphs, varying in data size based on the application, software, and intended use cases. The application perspective includes examining CBIM technologies that facilitate collaboration, practices encouraging or hindering team collaboration, and data governance strategies for secure and efficient data usage (Mutis and Mehraj, 2022).

Table 1. The applications of CBIM and the addressed information quality problems.

2.2. Information Quality

While BIM, whether desktop-based or cloud-enabled, has been proven as an efficient and collaborative method for managing and storing information in project delivery and the use phase, it is important to note that the technology itself does not automatically assure the quality of the embedded information (Pärn *et al.*, 2016). Since essential building information predominately originates from construction projects, the effective realisation of sustainability objectives through BIM hinges critically on the quality of information fed into the system (Pinheiro, 2019). Subsequently, the management of this information across the entire lifecycle of the physical assets plays a pivotal role in ensuring the success of these sustainability goals.

Information quality is a complex and multi-dimensional concept without a universally accepted set of dimensions and related definitions of each dimension (Wand and Wang, 1996; Woodall *et al.*, 2013). The quality of information is assessed based on its ability to consistently meet user expectations and requirements (e.g., sustainability), a subjective measure that varies by context (Pringle *et al.*, 2002; Strong *et al.*, 1997; Wang and Strong, 1996). Effective information management addresses this through the entire information lifecycle, including its creation, organisation, storage, distribution, and use (DAMA International, 2017). Commonly cited dimensions in literature are accuracy, completeness, consistency, and timeliness (Chang *et al.*, 2022; Woodall *et al.*, 2013):

- Accuracy: Information reflects the actual value.
- Completeness: All required information is present to meet the user's requirements.
- Consistency: The absence of difference when comparing multiple information.
- Timeliness: Information is sufficiently current for the task at hand.

Further elaborating on information quality problems, Ge and Helfert (2007), drawing from previous studies, classified information quality issues into two categories: (1) context-independent and context-dependent. Context-independent problems are those that occur irrespective of the specific situation or application, including issues like spelling errors, data omission, duplications, inconsistent formats, and incorrect values (Eppler, 2006; Oliveira *et al.*, 2005). Conversely, context-dependent problems are those that arise in response to specific situational or contextual factors, with violation of company and government regulations serving as a prime example (Pipino *et al.*, 2002). Additionally, the same authors evaluated these issues from two distinctive lenses: the user perspective, which focuses on problems identified by information consumers, and the data perspective, which addresses issues that are inherent to the data itself, independent of any specific user's viewpoint (See Table 2).

Table 2. Categorisation of information quality problems

Leveraging the information quality problems listed in Table 2, this study explores CBIM's contributions to preventing quality deterioration and ensuring the quality of asset information.

3. Methodology

This research argues that inductive theory generation on CBIM capabilities requires an in-depth understanding of CBIM's inherent limitations through those who help develop this tool. Therefore, this research employed a mono-method qualitative approach, leveraging semi-structured interviews with software engineers. A sample of software engineers proficient in developing technological solutions for the AEC industry was selected. This deliberate choice facilitated an in-depth analysis of their unique viewpoints, providing technological capabilities and efficiency of CBIM in handling quality asset information.

3.1. Sampling and recruitment

Using the purposive sampling technique described by (Lucas, 2014), this study engaged 13 participants from software solution providers in the US, UK, Finland and Germany. To ensure that the sample represents the population, potential participants were required to develop technological solutions for the AEC industry, with a specific focus on cloud technology. Table 3 details the profiles of the participants engaged in the interviews.

3.2. Data collection

Semi-structured interviews were chosen as the primary data collection method. Interviews were more valuable than the survey in meeting the aim of this study because they allowed participants to share experiences on the subject under investigation. Before the interviews, the questions were systematically categorised into three main groups: (1) the advantages of leveraging CBIM for effective information management, (2) the prevalent technological barriers faced by CBIM, and (3) the ramifications of employing CBIM in the domain of asset information management. Questions about the advantages of CBIM were instrumental in illuminating its strengths and potential openings for innovation and improvement. Subsequently, questions addressing technological challenges revealed the limitations intrinsic to CBIM, especially concerning managing diverse asset information predominately rooted in current technological constraints.

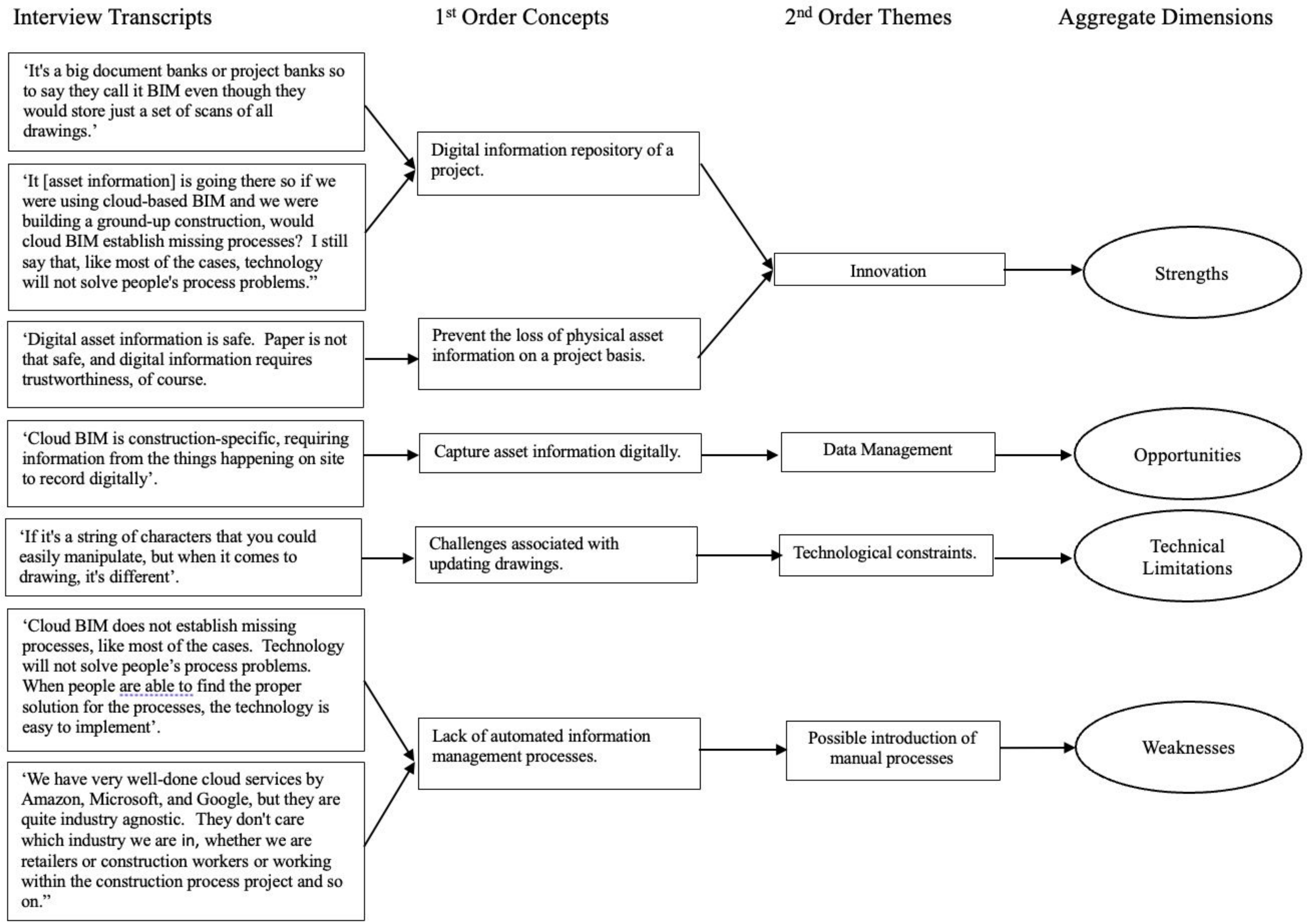
Table 3. List of participants

Participants had the option to skip questions deemed irrelevant or sensitive, particularly those proving current product development specifics. Interviewing continued until data saturation was reached, meaning no new information emerged from participants, as Easterby-Smith *et al.* (2021) suggested. Interviews averaged 60 minutes. With prior consent, all interviews were recorded and later transcribed for detailed analysis.

3.3. Data analysis

The data analysis followed the steps of thematic analysis recommended by Gioia *et al.* (2013). Firstly, the interviews were coded using NVivo, a qualitative analysis software, augmented by extensive notetaking to transform the raw data into 69 preliminary concepts. Each researcher performed independent coding of the interviews reflecting the terminology used by participants. Next, the researchers refined the coding scheme. Subsequently, the study performed a data reduction process, eliminating redundant concepts, discarding categories irrelevant to the research question, and merging categories into 16 second-order themes (Gioia *et al.*, 2013; Grodal *et al.*, 2021). The final cycle culminated in consolidating these themes into 4 broader dimensions: strengths, weaknesses, opportunities, and technical limitations.

To demonstrate the data analysis process, Figure 1 provides an example from an interview, illustrating the steps involved in processing interview data. Initially considered raw data, the interview transcript undergoes categorisation into ‘first-order concept’, which emerges as 69 categories from an analysis of 13 interviews. These first-order concepts are further refined into ‘second-order themes’, such as ‘Innovation’, ‘Data Management’ and ‘Technology Constraints’, totalling 16 themes. These second-order themes are then evaluated to identify ‘Strengths’, ‘Weaknesses’, ‘Opportunities’, and ‘Technological Limitations’.



‘It's a big document banks or project banks so to say they call it BIM even though they would store just a set of scans of all drawings.’

‘It [asset information] is going there so if we were using cloud-based BIM and we were building a ground-up construction, would cloud BIM establish missing processes? I still say that, like most of the cases, technology will not solve people's process problems.”

‘Digital asset information is safe. Paper is not that safe, and digital information requires trustworthiness, of course.

‘Cloud BIM is construction-specific, requiring information from the things happening on site to record digitally’.

‘If it's a string of characters that you could easily manipulate, but when it comes to drawing, it's different’.

‘Cloud BIM does not establish missing processes, like most of the cases. Technology will not solve people’s process problems. When people are able to find the proper solution for the processes, the technology is easy to implement’.

‘We have very well-done cloud services by Amazon, Microsoft, and Google, but they are quite industry agnostic. They don't care which industry we are in, whether we are retailers or construction workers or working within the construction process project and so on.”

Figure 1. An example of thematic analysis of an interview

Significant insights were distilled from the raw data, transitioning software engineers' feedback into an interpretive analysis that enriches understanding of CBIM's ability to manage quality asset information.

4. Results

This section presents CBIM's capabilities in managing quality asset information from the perspective of software engineers. Findings are derived from thematic analysis of interviews with anonymous coding (e.g., RQ3P1 and RQ3P2) to maintain confidentiality.

Adopting a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, findings are categorised into Strengths, Weaknesses, Opportunities, and Technological Limitations, with 'Threats' adapted to 'Technological Limitations' to better align with the focus of this study. Figure 2 illustrates the findings. Further, linking these findings with the information quality problems identified by Ge and Helfert (2007) are displayed in Figure 3.

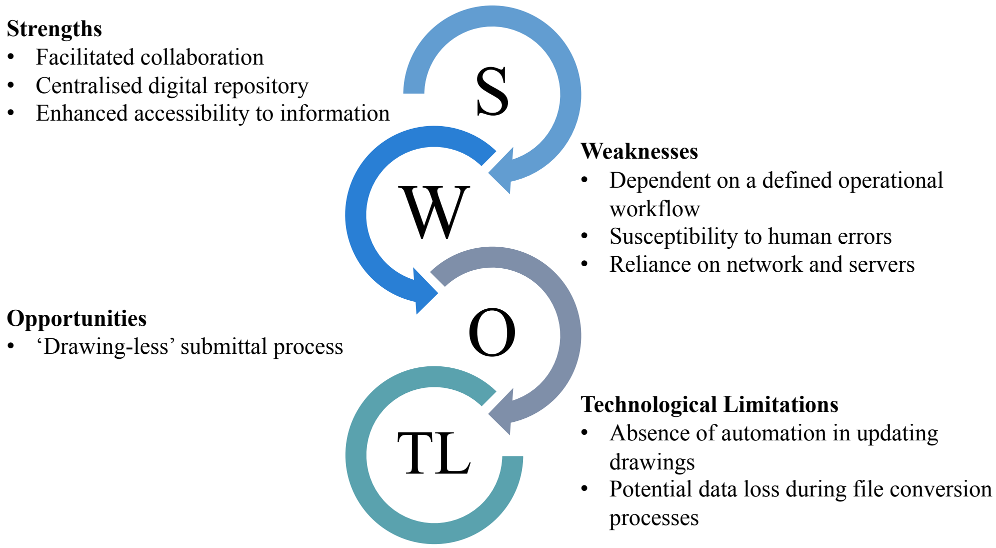


Figure 2. The capabilities of CBIM from software engineers' viewpoint

4.1. Strengths

The participants have identified three compelling strengths of CBIM, underscoring its vital role in enhancing asset information quality within the building sector: (1) enhanced collaborative design phase, (2) robust digital storage, and (3) accessibility.

The participants indicate that CBIM enhances *'collaboration during the design phase*', leading to generating quality design in construction projects (RQ3P1). As RQ3P12 elucidated, *'CBIM can orchestrate the multi-faceted information among the diverse project elements.'* The collaboration among project participants streamlines workflows, while fostering cross-domain collaboration to allow 'each *[design element]* is *uniquely identified, and its details are accurately represented in consistent manners'* (RQ3P3). This collaborative approach fosters the systematic representation of asset information, tailoring the uniqueness of each asset while distinctly expressing design details coherently (Liu *et al.*, 2020; Sacks *et al.*, 2022).

Another notable strength of CBIM as its innate ability for digital information storage, which integrates '*naturally in the cloud-based environments'* (RQ3P4). In this context, CBIM adeptly provides *'a single source of information containing multiple layers of mechanical, electrical, and architectural information*' in contrast to traditional compilations of information (RQ3P1). This system, acting as a robust repository for asset information, RQ3P2 underscored accessibility offered by CBIM, stating, '*Cloud-based BIM enables us to find a vast amount of information while providing easy access to those needs' information.* Moreover, *'When a new employee is onboard, one can just sort through the CBIM to find the necessary information' (RQ3P2).* Further, utilising CBIM as a centralised repository can reduce the risk associated with the loss of tangible information, such as drawings.

4.2. Weaknesses

CBIM offers considerable benefits, yet it simultaneously introduces a set of challenges. Participants have pinpointed key weaknesses: (1) an inability to define information management processes, (2) human errors due to the reliance on manual processes, and (3) the dependency of networks and servers. These shortcomings highlight managerial implications within the domain of CBIM.

Although adopting technological solutions can enhance efficiency when using them appropriately, they do not inherently establish an associated *'workflow*' (RQ3P7). Effective workflows are the structural pillars of any organised process, vital for executing tasks efficiently and uniformly. RQ3P2 notes that *'I feel strongly that technological solutions [software] do not define the workflows.'* Without well-defined workflows, asset information management via CBIM might not reach its full potential (RQ3P2). The lack of a methodical approach heightens the risk of introducing errors and operational inefficiencies, undercutting the potential benefits of the technology (RQ3P7). Consequently, while CBIM presents an opportunity to advance operational efficiency, it is incumbent upon organisations to devise and implement bespoke, robust workflows designed to align with and amplify the strengths of CBIM. As a result, software engineers asserted the need for a robust *'internal information management procedure'* to prevent the risk of information quality deterioration (RQ3P3, RQ3P5, RQ3P8, RQ3P11, & RQ3P13).

Additionally, CBIM's reliance on manual updates jeopardises asset information quality. As RQ3P7 indicates, *'All design elements are manually created during the design phase. Consequently, the quality of these design elements is directly proportional to the designers' expertise and attention to detail.'* Even during the use phase, CBIM depends on manual updates of existing asset information corresponding to various building projects, which are prone to *'human errors and oversights'* due to the lack of automated information update processes (RQ3P3). This deficiency is especially pronounced in the upkeep of as-built drawings, which are essential for accurate building representations as they guide various activities, including maintenance, renovations, and physical space management. Continuous quality assurance measures among project participants are necessary, requiring designers involved in each building project to approve the quality of handover information before it is updated.

Finally, the dependency on networks and servers is recognised as an additional weakness of CBIM. Continuous network connectivity emerges as a foundation for CBIM efficacy, where disruptions can cripple system functionality, a situation that is particularly acute in regions with inconsistent internet services (RQ3P8 and RQ3P10). Server dependency further compounds this risk. Server outages can result in a complete loss of access to vital asset information, leading to halted workflows and asset management activities. RQ3P12 also notes the critical risk of information loss stemming from server crashes. These dependencies introduce substantial risks of operational delays and inefficiencies. As such, there's a pressing need for CBIM to develop resilient data management capabilities, including *'implementing redundant system'*, *'crafting offline functionality'* or *'exploring decentralised data storage solutions'* (RQ3P6, RQ3P7 and RQ3P13).

4.3 Opportunities

RQ3P4, RQ3P9, and RQ3P10 collectively highlighted the transformative opportunity in facilitating a 'drawing-less process' in the submittal procedures. The traditional submittal process, characterised by a sequential approval mechanism required prior to fabrication commencement, is undergoing transformative changes. ‘*For example, the contractor can submit structural details, such as the I-beam and associated connector details, directly through CBIM for the structural engineer’s approval without generating hard copies of submittal drawings and the associated material specifications. ‘The accessibility of 3D models on laptops and tablets has revolutionised the submittal process’, as articulated by RQ3P4.* Additionally, once submittals receive approval, they are readily available in an electronic format for fabrication purposes. RQ3P10 further stated that ‘*this shift towards a drawing-less [object-based] process is substantiated for national highway projects in the Nordic countries’*. This exemplifies the opportunities and efficiencies offered by digital submittal processes in the building industry facilitated by CBIM. It markedly reduces potential issues related to information quality and guarantees the effective distribution of information across stakeholders.

4.4. Technological Limitations

Despite CBIM’s innovative opportunities, software engineers pointed out technological constraints in managing asset information quality: (1) a lack of an automated process of updating as-built drawings and (2) information loss during the file conversion.

RQ3P1 elucidated, ' *The concept of CBIM is using BIM software on cloud services, without appropriate automated information flow processes.* If *it is a string of characters [non-graphical information], you could easily manipulate to update the information using Excel, but when it comes to drawings, it is different’. We currently do not have an automated process for updating as-built drawings to reflect onsite modifications.’* To illustrate this point, non-graphical information, such as the models, makers, and serial numbers of installed building components, can be extracted into a tabular format, such as an Excel spreadsheet, to facilitate transferring purposes. However, any modifications to the current as-built drawings require updates within the original file format, such as a Revit model. Countering this perspective, RQ3P9 presents the *‘point cloud scanning technique’*. However, this method encounters limitations, including extensive data processing time, scalability, and its restriction to capturing spatial information, omitting essential details in enclosed areas, such as pipes behind walls or above ceilings.

In addition, RQ3P6 elaborated on inherent problems of information loss due to technological constraints. This problem is exemplified in the process of ‘*converting a 3-dimensional model to a 2-dimensional plan, where the conversion fails to transfer the embedded information within the* *objects to the plan',* underscoring a significant challenge posed by technological constraints. Typically, a 3D model is converted into 2D plans in AutoCAD format, which are widely utilised for construction and space utilisation purposes. However, it is crucial to understand that while dimensional modifications and configurational updates of 2D plans in AutoCAD format may capture spatial alterations, they do not synchronise updates related to essential attributes, such as wall types and thickness, in the corresponding 3D model. Delving this issue with a technical lens, RQ3P3 illustrated a prevalent information issue of information loss through practical applications: *'Using IFC, for example, we first map data from source X to IFC Y, and then when reading data from IFC to application Z, we do another conversion. There are two opportunities for information loss. Even if the information could be presented both in X and Z but not in the intermediary format Y, the information is lost even though a direct link between X and Z could perform the mapping'.* This explanation highlights the challenge of maintaining coherent and up-to-date asset information across different model formats.

4.5. CBIM's capabilities to address information quality problems

This section provides an analysis of CBIM's effectiveness in addressing the quality issues identified by Ge and Helfert (2007), as depicted in Figure 3. The analysis suggests that CBIM is proficient in correcting context-independent data issues such as spelling and syntax errors. Yet, its effectiveness is less assured when it comes to complex problems like the absence of necessary data or incorrect values, indicating a need for improving data validation functions. From the user's standpoint, CBIM is effective in providing access, retrieval, and secure storage of information, facilitating fundamental user interactions. Nevertheless, it struggles with transforming data into more user-friendly formats without compromising data integrity, reflecting a crucial area for enhancement. These observations signal that while CBIM competently addresses certain information quality issues, it requires further refinement to meet the demands of context-independent information management and user experience.

Conversely, Figure 3 reveals that there were no specific information quality issues directly attributable to CBIM from the context-dependent data perspective. However, it becomes evident that CBIM is limited to resolving information quality problems to meet specific situations or user requirements. This shortfall calls attention to the need to optimise resource distribution, analyse business challenges, re-engineer processes, and re-align information flow from sources to address problems effectively (Ge and Helfert, 2007).

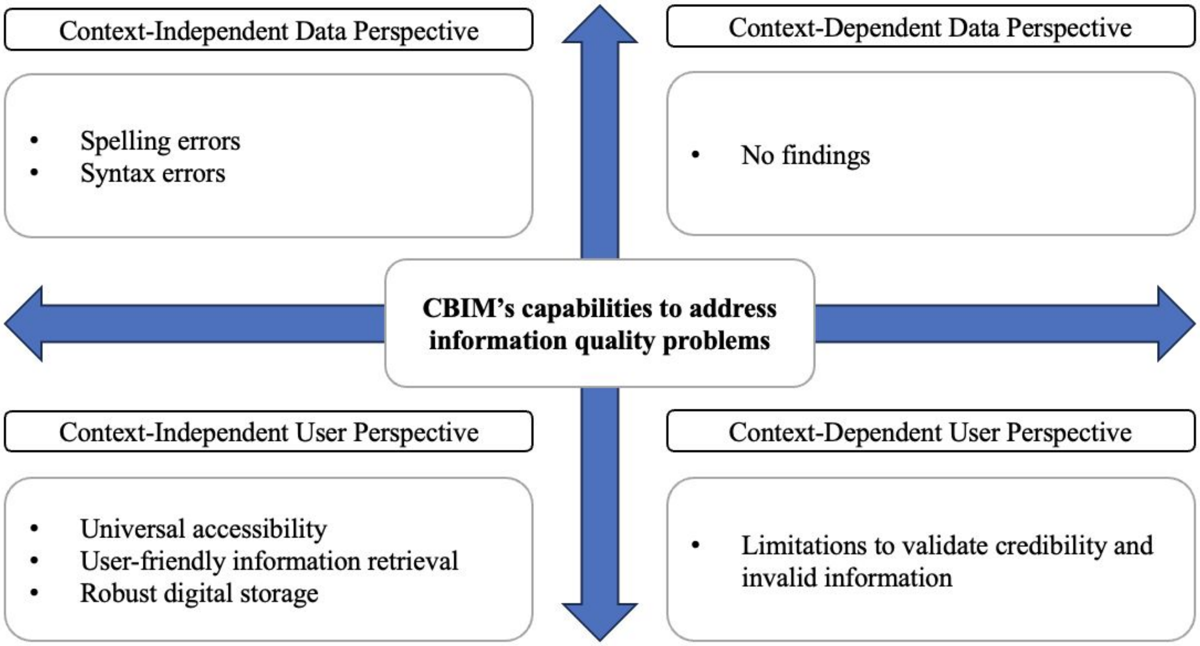


Figure 3. A summary of CBIM's capabilities in asset information management

The SWOT analysis reveals various dimensions of CBIM's capabilities while highlighting its ability to validate context-dependent user perspective issues requires managerial oversight.

5. Discussion

This research has elucidated CBIM's capabilities in addressing information quality problems through the lens of software engineers developing technological solutions for the AEC industry. Understanding the intrinsic technological limitations is vital for optimising its potential in information management. Building on these insights, this section discusses contributions to theory and practice, acknowledges methodological limitations and provides suggestions for future studies.

~~5.1. Key findings~~

~~The synthesis of findings from the literature review and the interviews with software engineers reveals a multifaceted view of CBIM's role in enhancing handover information quality. While the literature emphasises CBIM's contribution to mitigating quality issues during the design phase, the interview results caution against over-dependence due to tangible limitations, advocating for a balanced approach to CBIM's technological potential and practical challenges. Consequently, targeted efforts in technological refinements and procedural~~

~~optimisations are necessary to address these issues. Despite challenges, CBIM is pivotal in facilitating efficient information exchange and enhancing project data quality. Strategic management and continuous improvement are crucial to address its operational vulnerabilities and maximise its capabilities to improve handover information quality.~~

5.1~~2~~. Theoretical contribution

The theoretical contribution of this research lies in its deep exploration of the dynamic interplay between CBIM and asset information management, specifically addressing the complex challenges faced in preventing factors leading to the deterioration of handover information quality. This research acknowledges the capabilities of CBIM in enhancing collaborative design practices, a point underpinned by the findings of Sacks *et al.* (2022), yet it goes further to identify and theorise on the operational challenges, particularly the risk of information loss during the design phase due to data conversion across disparate BIM software formats (Sacks *et al.*, 2018). These operational challenges are not merely technical issues; they reflect deeper systemic issues faced in the AEC industry, as argued by (Singh, 2019). For example, when multiple BIM applications are involved, the incompatibility between data structures can lead to significant information deterioration. This is not just a technological limitation of CBIM; it also poses a substantial risk to the reliability of handover information, which is critical for the operational integrity of physical assets (Matarneh *et al.*, 2022).

As such, this research proposes an 'Integration Theory of CBIM and Asset Information Management', which advocates for a lifecycle-oriented approach to information quality. This approach recognises the necessity of integrating CBIM practices within a broader asset management strategy to align with the quality expectations of information users (Ge and Helfert, 2007). It advocates for context-specific processes that integrate CBIM, enabling ~~calls for developing and deploying~~ automated quality control mechanisms that utilise advanced analytics, machine learning, and artificial intelligence to not only reactively identify but also proactively predict and mitigate potential deterioration in information quality (Zabin *et al.*, 2022; Zhang, 2020). Moreover, the theory introduces the concept of adaptive learning systems embedded within CBIM, which are designed to refine information management practices by learning and evolving based on ongoing feedback and information. This adaptability is crucial in a field characterised by constant change and evolution, where asset information must be as dynamic and responsive as the environments in which it is applied.

By proposing this theory, the research seeks to broaden the existing theoretical landscape of asset information management to include elements specific to CBIM, such as the capacity for real-time updates, the cultivation of collaborative environments beyond the design phase, and the strategic use of digital twins to optimise the management of physical assets. The theory positions CBIM not as a mere repository or static tool but as a dynamic facilitator of asset management, potentially bringing about significant enhancements in the efficiency of asset management, sustainability, and adaptability. In envisioning a holistic integration of CBIM within asset management, this research sets forth a theoretical framework that aims to provoke a paradigm shift toward more efficient and sustainable practices in the built environment. This paradigm shift requires overcoming significant challenges, including ensuring interoperability across diverse BIM tools, developing predictive analytics for quality control, and fostering an industry-wide acceptance of these advanced methodologies.

5.2~~3~~. Practical relevance

Grounded in the ‘Integration Theory of CBIM and Asset Information Management’, this theory advocates for a lifecycle-centric approach underpinned by continuous adaptation and feedback mechanisms. These mechanisms are essential for enhancing asset information quality through CBIM. A practical application of this theory is developing an advanced collaborative platform designed to support CBIM activities. From the perspective of technological solution providers, this innovation facilitates using cloud-based storage to support multiple products from the same company, eliminating the need to transfer project data from one solution to another. Such an approach reduces errors caused by human intervention and the potential loss of information during the file import and export processes. Simultaneously, this model enables end-users to leverage analytics for various asset management activities, fostering informed decision-making underpinned by quality asset information. This paradigm shift propels asset management from traditional, static practices to dynamic, feedback-driven processes that are emblematic of adaptive learning principles.

Moreover, managing as-built drawings can benefit from incorporating automated quality control mechanisms that resonate with the proposed theoretical insights. Innovations such as CBIM plugins utilising emerging scanning techniques to automate updates to as-built drawings are pivotal. They can mirror real-time modifications, aiming to minimise manual processing for drawing updates, reduce human errors, and ensure the quality of as-built drawings.

Further, overcoming challenges related to internet connectivity, especially in less developed or rural areas, involves harnessing the capabilities of digital twin technologies. This approach is bolstered by advancements in 5G technology and the anticipation of 6G networks. It aligns with the theory's advocacy for real-time updates and collaborative environments, illustrating the practical application of theoretical concepts into tangible, actionable strategies. Integrating digital twins with CBIM optimises the asset management process, rendering it more efficient, sustainable, and adaptable to the evolving dynamics of the built environment.

Embedding these practical recommendations presents a visionary strategy for employing CBIM in asset management. It illustrates how theoretical insights can catalyse significant practice transformation, establishing a new standard for efficiency, sustainability, and adaptability in the built environment. Beyond the AEC industry, sectors such as civil engineering, infrastructure, transportation, aviation, manufacturing, real estate, urban planning, and smart city initiatives stand to benefit from these recommendations. Implementing these recommendations promotes an environment where the potential of CBIM can be fully realised, facilitating various activities with quality asset information.

5.34. Limitations and suggestions for future research

The exploration of CBIM in the AEC industry, primarily from software engineers' perspectives, presents vital insights into its capabilities and limitations within asset information management. However, this concentration limits the exploration to a singular viewpoint, potentially missing the broader spectrum of challenges and opportunities perceived by the end users, such as asset management professionals. While rich in detail, this research's qualitative nature constrains the conclusions' scalability and generalisability. Notably, the technical hurdles highlighted, including information loss during file conversions and the absence of automated updates for as-built drawings, underscore the need for technological advancements and highlight the complexity of implementing CBIM in real-world scenarios.

Future research into CBIM must broaden to include diverse stakeholder perspectives, including end-users and regulatory bodies, enhancing insights into CBIM's utility during the use phase of buildings. Integrating quantitative methodologies, such as surveys and case studies, will complement existing qualitative insights, offering a detailed view of the effects of CBIM on asset information quality and operational efficiency. Addressing technological advancement is critical, focusing on developing algorithms and machine learning techniques for automating information updates and minimising information loss during file conversions. This technological push should be accompanied by efforts to enhance software interoperability, ensuring consistent information quality throughout the asset's lifecycle. Moreover, constructing comprehensive frameworks for CBIM implementation and conducting longitudinal studies will be vital. This framework should incorporate best practices for information management and stakeholder collaboration, while longitudinal studies could reveal CBIM's long-term sustainability and economic benefits, providing a holistic view of its potential enhancement and efficiency.

6. Conclusions

This study critically evaluated the application of CBIM in the building sector, focusing on its capabilities in managing information quality, as perceived by software engineers. Key findings of this research indicate that while CBIM can address context-independent quality problems such as spelling errors and digital storage, it requires additional managerial oversights and strategic operational adjustments to exploit its potential fully. A comparative review of these findings with existing literature reveals that although adopting CBIM is widespread in the AEC industry, the focus largely remains on technological advancements rather than on its integration into broader information management processes, a discrepancy that highlights a significant area for future research. This study extends the current understanding of CBIM's capabilities by highlighting the necessity for continuous quality assurance and adopting advanced technological strategies to overcome CBIM's limitations. Moreover, it emphasises the importance of refining CBIM integration strategies and procedural optimisations to address these challenges effectively. Therefore, strategic management and continuous improvement are crucial to address its operational vulnerabilities and maximise its capabilities to improve handover information quality.~~Recognising the prevalence of CBIM in the building sector, this study identified CBIM's capabilities in managing quality through the lens of software engineers to understand the technological boundaries that might limit its application. Despite its benefits, CBIM encounters several challenges that require managerial oversights and innovative operational strategies to harness its full potential. Addressing these challenges, this research underscores the importance of continuous quality assurance and the utilisation of technological advancement to overcome CBIM's existing limitations. Further research is crucial to maximise CBIM's contribution to optimising asset information quality and enhancing efficiency and sustainable practices in the built environment.~~

532 7. Acknowledgement

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Response to reviewers' comments to BEPAM-12-2023-0247
Please use the **BEPAM-12-2023-0247.R2_Final_no track change_06232024** document to reference line numbers.

Dear Drs Rodrigo, Sridarran & Reviewers,
We are grateful that you have given us an opportunity to refine the manuscript. Your constructive feedback has undoubtedly improved the quality of our work. Thank you again for considering our work.

Reviewer 1

Item	Categories	Reviewer's comment	Corresponding line numbers	Response
1		The authors have addressed all comments. However, I'd suggest linking the outcomes of this paper back to existing literature (currently there is only one - Sacks et.al).	BEPAM-12-2023-0247.R2_Final_no track change_06232024 Lines 408 – 409, Line 410, Lines 416 – 419, Line 419, and Line 422.	We link the outcomes of this research to the following literature: Lines 408 – 409 (Sacks et al., 2018) Line 410 as argued by (Singh, 2019) Line 414 (Matarneh *et al.*, 2022) Lines 416 – 419 This approach recognises the necessity of integrating CBIM practices within a broader asset management strategy to align with the quality expectations of information users (Ge and Helfert, 2007). Line 419 It advocates for context-specific processes that integrate CBIM Line 422 (Zabin *et al.*, 2022; Zhang, 2020)

				Please see the updated text in the revised manuscript.

Guest Editor' Comments

1A	Summary of key findings in Conclusion	Please provide a summary of key findings in Conclusions.	BEPAM-12-2023-0247.R2_Final_no track change_06232024 Line 401, Line 440, Line 474	We eliminated Section 5.1 Key findings to conclusion. Due to this change, we updated the numbering of the subsections in the discussion sections: Line 401 5.1. Theoretical contribution Line 440 5.2. Practical relevance Line 474 5.3. Limitations and suggestions for future research
1B	Conclusion	As implications to theory and practice as well as limitations and future research directions have been moved to Discussion, the conclusion does not look strong. Therefore, I would recommend to expand the discussion session a little bit by comparing your findings with existing literature. Afterwards move implications to theory and practice, limitations and future research directions, to Conclusions section.	BEPAM-12-2023-0247.R2_Final_no track change_06232024 Lines 498 - 512	We revised the conclusion including key findings of this research: This study critically evaluated the application of CBIM in the building sector, focusing on its capabilities in managing information quality, as perceived by software engineers. Key findings of this research indicate that while CBIM can address context-independent quality problems such as spelling errors and digital storage, it requires additional managerial oversights and strategic operational adjustments to exploit its potential fully. A comparative review of these findings with existing literature reveals that although adopting CBIM is widespread in the AEC industry, the focus largely remains on technological advancements rather than on its integration into broader information management processes, a discrepancy

				that highlights a significant area for future research. This study extends the current understanding of CBIM's capabilities by highlighting the necessity for continuous quality assurance and adopting advanced technological strategies to overcome CBIM's limitations. Moreover, it emphasises the importance of refining CBIM integration strategies and procedural optimisations to address these challenges effectively. Therefore, strategic management and continuous improvement are crucial to address its operational vulnerabilities and maximise its capabilities to improve handover information quality.

Table 1. The applications of CBIM and the addressed information quality problems.

Purpose	BIM format	Data transmission	Reference	Addressed Information quality problems
Facilitate collaborative design in the construction projects by ensuring model consistency and object-level version control.	RDF graphs from IFC files	Not specified, but transfer BIM sub-graphs for explicit federated	Sacks *et al.*(2022)	Design accuracy, consistency, and completeness.
Enable facility management users to retrieve and transfer various data sources seamlessly into facility management systems.	IFC files parsed into a relational database (Microsoft SQL Server)	Cloud SQL server	Matarneh *et al.* (2022)	Improved data accessibility and accuracy in facility management systems
Foster digital collaboration among stakeholders for generating the projects' Green Mark score, meeting regulatory standards.	IFC2x3	Custom cloud platform, as a common data environment for the Green Mark scheme	Liu *et al.* (2020)	Design accuracy and regulatory compliance.
Introduce a system for real-time BIM-VR synchronization system, updating VR headsets with BIM changes instantly.	Autodesk Revit	Customised cloud server and database	Du *et al.* (2018)	Accuracy and timeliness of the information.
Provide a web-based service for viewing, storing, and analysing extensive building information models.	MapReduce for IFC files, saved in cloud database	Apache Hadoop with Bigtable-like storage on distributed servers	Chen *et al.* (2016)	Centralised information repository to minimise information loss, ensuring accuracy, and accessibility.
Enhance communication efficiency among project participants to improve design quality and reduce rework.	Entire or partial IFC building models	Amazon Elastic Compute Cloud (EC2) hosting BIM information within NoSQL databases	Das *et al.* (2015)	Design accuracy, consistency, completeness and timeliness.
Facilitate timely information access for monitoring progress and managing the construction of a reinforced concrete (RC) structure	Autodesk Revit	Autodesk BIM 360	Matthews *et al.* (2015)	Accuracy, completeness, and timeliness to update RC construction progress.

Table 2. Categorisation of information quality problems, adapted from Ge and Helfert (2007).

	Context-independent	Context-dependent
Data perspective	• Errors in spelling. • Absence of necessary data. • Incorrect value. • Repetition of data. • Data formats that are not uniform. • Syntax errors. • Violation of integrity rules. • Diverse units of measurement. • Presence of synonyms and homonyms	• Breach of domain constraints. • Infringement of the organisation's business rules. • Non-compliance with company and government regulations. • Violation of constraints provided by the database administrator.
User perspective	• Access to information is unattainable. • Information is insecure. • Retrieving information is challenging. • Compiling information poses considerable difficulties. • Transforming information is prone to inaccuracies.	• The information lacks factual grounding. • The credibility of the information is questionable. • The information offers a biased perspective. • The information bears no relevance to the task at hand. • The information is not comprehensive. • The information is presented in a condensed format. • The information is challenging to alter or use. • The information is difficult to comprehend. • The information is no longer current.

Table 3. List of participants

Participant ID	Job title	Experience (years)	Types of organisations	Location
RQ3P1	Data Enterprises	17	Industrial technology solutions	US
RQ3P2	Vice President, Digital Solutions	25	Industrial technology solutions	US
RQ3P3	Director Digital Products	32	Industrial technology solutions	US
RQ3P4	Distinguished Software Engineer	25	Industrial technology solutions	US
RQ3P5	Vice President, Design Solutions	27	Industrial technology solutions	US
RQ3P6	Co-Founder of Digital Products	20	Applications & software developer	UK
RQ3P7	Software Engineer/Consultant	15	Industrial Technology Solutions/Digital Consulting	UK
RQ3P8	Senior Software Engineer	19	Industrial technology solutions	Finland
RQ3P9	Distinguished Software Engineer	33	Industrial technology solutions	Finland
RQ3P10	Software Engineer	5	Industrial technology solutions	Finland
RQ3P11	Software Engineer	18	Industrial technology solutions	Finland
RQ3P12	Software Engineer	5	Industrial technology solutions	Germany
RQ3P13	Chief Executive Officer	18	Industrial technology solutions/Digital Consulting	Germany