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REVIEW ARTICLE

Incorporating smart objects into BIM: A comprehensive review

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Abstract

Smart objects, equipped with a variety of intelligent features, can significantly improve BIM efficiency and address issues such as data loss and outdated information throughout the design, construction, and management phases of projects. A systematic literature review was conducted, encompassing research articles published from 2005 to 2023, to examine the involvement of smart objects in BIM integration. Out of the 98 studies identified, it was revealed that smart objects play a crucial role in three primary stages of BIM implementation: pre-construction (architectural design), construction (management and progress monitoring), and post-construction (applications in smart buildings and documentation of existing and historical buildings). A comprehensive analysis of these studies led to the development of a current workflow, detailing the various categories of smart objects, their application areas, and the procedures involved in their creation. The analysis also provides insights into the methodologies, tools, and software crucial for BIM integration, along with potential challenges that may arise. It is anticipated that the use of smart objects as representatives of real building elements will become a core component of the AEC industry.

1. Introduction

Since the early 1980s, various industries have employed computer-aided design techniques. The field of architecture experienced a notable transformation in the 1990s with the introduction of Building Information Modeling (BIM), signing the next paradigm shift [1]. The term 'BIM' first appeared in 1992 [2], but it gained considerable popularity in the early 2000s when Autodesk published a paper titled "Building Information Modeling." This marked the onset of widespread adoption in the field, with other software providers also entering the scene [3]. The most noticeable distinction between BIM and traditional modeling methods lies in the fact that architects and engineers could collaborate within a shared data environment. This facilitates effective data access throughout the project's life cycle; encompassing design, construction, and post-construction phases [4, 5]. BIM can be characterized as an evolutionary phase of an intelligent model rather than a mere technology [6].

BIM comprises a well-organized assembly of data presented in a comprehensive building model [7]. The building data defines the information of design objects and their relationships with other model elements. Model objects function as digital replicas of real-world elements like windows, walls, or beams, and they can be categorized as non-parametric, parametric, or smart. Parametric design relies on the capacity to modify an object's

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attributes without the need for a complete redraw, underscoring the significance of objects having the appropriate behavior and knowledge to adapt and respond as necessary [8]. Smart objects go beyond parametric objects. These entities inherently comprehend their identity and have the capability to interact with other objects. They are distinguished by their parametric and intelligent attributes [9]. According to Ibrahim and Krawczyk [8], these components have the capability to encapsulate 'intelligence' and 'knowledge' by integrating design constraints, behavioral aspects, and features related to the lifecycle data flow directly into the objects themselves. For example, in design-stage projects utilizing cloud computing, when a smart object, like a wall, undergoes changes, it transmits this information to other interconnected objects, such as beams, ensuring their concurrent update as well [10]. Therefore, smart objects enhance the efficiency of BIM and offer solutions to issues such as data loss and outdated information during the design, construction, or management phases of projects.

Smart objects appear with various names at different stages of BIM projects, including smart objects, smart BIM objects, smart building objects, smart construction objects, smart building elements, smart elements, and BIM objects. Basically, they all serve a common purpose; integrating data, establishing diverse connections within the environment, and accurately representing their functions in real-world scenarios [11]. Since these intelligent components possess the capability to not only provide their distinct identification and status details but also engage in communication with other objects, they enable "ad-hoc networking" and facilitate "object-centric complex decision-making" [12]. The notion of ad-hoc information sharing involves the ability of smart objects to transmit their awareness to other smart objects through intercommunication, as well as to convey such information to individuals [12, 13, 14, 15]. Smart objects have the capacity to encompass various dimensions of information, essential for facilitating multidisciplinary perspectives on the objects. In certain studies, the intelligence of these objects arises from the transfer of real-world data to the digital model and continuous synchronization to ensure the model remains up-to-date. To augment the intelligence of building components, further parametric and automated features are being integrated into BIM models through the application of data sharing technologies like cloud computing and sensor technologies such as the Internet of Things (IoT).

The primary objective of this study is to comprehensively present all stages encompassing the production and utilization process of smart objects. To date, no research has offered a holistic depiction of the entire life cycle of smart objects. This review explores key concepts, platforms, and technologies associated with smart objects, aiming to serve as a fundamental resource for architects, engineers, BIM modelers, and other participants in Architecture, Engineering and Construction (AEC) industry.

A 'Systematic Literature Review' (SLR) was employed to investigate the role of smart objects in BIM integration. Utilizing this methodological approach, the paper defines the methods, techniques, and attributes associated with smart objects. Studies that achieved precise assumptions and outcomes were identified and analyzed. The obtained results were used to unveil the application goals and processes of smart objects, encompassing both their possibilities and constraints –spanning their development from inception to the present day.

2. Methodology

The method known as SLR serves as a tool for identifying, analyzing, and interpreting relevant information related to a specific subject, research problem, or noteworthy event [16, 17]. The primary reasons for conducting a SLR include summarizing existing evidence on the subject, identifying shortcomings in current techniques, proposing areas that require further investigation, and establishing a foundation for effectively positioning new research endeavors [18].

This study adhered to the review process definition established by Kitchenham and Charters in 2007 [16]. The methodological approach aims to scrutinize and organize studies, systematizing the procedure through a sequence of five phases: 'Research Questions,' 'Search Strategy,' 'Study Selection,' 'Data Extraction,' and 'Data Synthesis.' These subsections provide a detailed account of the review protocol's specifics. In the 'Research Questions' subsection, the inquiries targeted by the SLR are outlined. The 'Search Strategy' subsection delineates the research approach, including search terms and sources used to identify relevant studies. In the 'Study Selection' subsection, criteria for inclusion and exclusion are defined based on the research questions. The 'Data Extraction' subsection formulates a checklist for addressing research questions and collecting relevant data. Finally, the 'Data Synthesis' subsection categorizes studies to assess and amalgamate primary study outcomes.

2.1. Research questions

The main objective of this SLR is to map the usage of smart objects in the context of BIM integration. Existing literature has examined this subject from diverse perspectives. To fulfill this goal, five research questions (RQs) have been formulated. RQ1 aims to analyze the types of smart objects in BIM, while RQ1.1 further explores these aspects. RQ2 defines computational techniques and parameters associated with smart objects. RQ3 and RQ3.1 discuss the tools used for data extraction and how smart objects interact with users or the environment. RQ4 investigates BIM implementation with case-based features. Table 1 presents the RQs and their rationales, providing a tool to evaluate the suitability of studies for inclusion in the review.

2.2. Search strategy

The search strategy relies on a set of keywords to comprehensively explore all available literature resources. These keywords are formulated by combining terms using 'OR' and 'AND' operators to refine the search results. These keywords are Building Information Modeling (OR BIM) AND smart objects (OR smart construction objects OR smart components OR smart building objects OR smart building elements OR BIM objects OR BIM components OR smart BIM objects) OR Smart Building (OR smart home OR smart environment). The keywords were searched within the eight most frequently used academic databases: Google Scholar, Science Direct, Web of Science, Springer Link, ACM Digital Library, Wiley Online Library, IEEE Xplore, and JSTOR. Table 2 displays the dates indicating when searches were conducted within academic databases. The search was limited to the period from 2000 to 2023. Fig. 1 illustrates both the number of studies retrieved from the databases and the workflow of the process based on the search results. The initial search concluded with 625 candidate papers, which were then reviewed, and any duplicate papers were eliminated.

Table 1. Research questions

Number	Research Questions	Motivation
RQ1	Which is the naming of Smart Object?	Identifying the smart objects according to project stages
RQ1.1	What is the function of Smart Object?	Identifying the usage areas of the smart objects
RQ2	Which software program is used for smart objects modeling?	Defining which software is used for this process
RQ3	Which tools are utilized for data acquisition?	Investigating commonly used tools
RQ3.1	How do smart objects interact with the user or environment?	Identifying communication methods
RQ4	Is there a case study?	Recognizing the significance of real-world application in research

Table 2. Academic databases and research dates

Database Name	Ref No	First Search Date	Second Search Date
Google Scholar	[106]	10 Oct-19 Nov 2022	25 Oct 2023
Science Direct	[107]	27-31 Nov 2022	25 Oct 2023
Web of Science	[108]	10-28 Sep 2022	26 Oct 2023
Springer Link	[109]	20-22 Nov 2020	26 Oct 2023
ACM Library	[110]	8 Nov 2022	26 Oct 2023
Wiley Online Library	[111]	9-12 Dec 2022	26 Oct 2023
IEEE Xplore	[112]	13-15 Dec 2022	26 Oct 2023
JSTOR	[113]	16 Dec 2022	26 Oct 2023

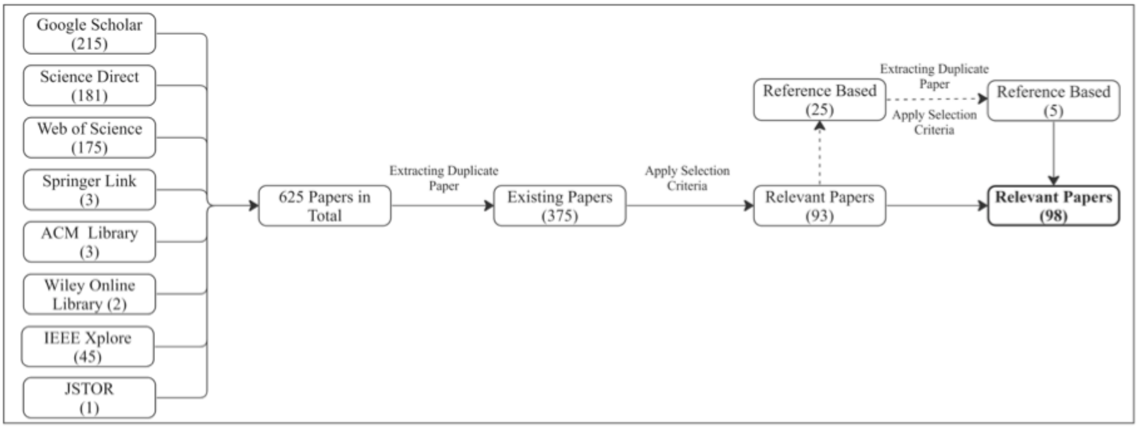

Fig. 1. Study selection process

2.3. Study selection

After the initial search and the removal of duplicate papers, a total of 375 studies were obtained. To refine our selection, inclusion and exclusion criteria were established. Two researchers independently reviewed the titles, abstracts, conclusions, and, when necessary, the full texts of the identified studies. Any conflicts between the researchers were resolved through discussions. Subsequently, 93 studies were identified for further analysis as a result of this selection process (Fig. 1). The selection of candidate studies was based on the inclusion and exclusion criteria outlined below:

Inclusion Criteria:

- Studies presenting empirical data, experiments or case analyses related to smart objects.
- Studies discussing a variety of smart object types in various application areas
- Studies explicitly addressing smart objects within the context of BIM.
- Only peer-reviewed journal articles, conference papers, and other scholarly publications.

Exclusion Criteria:

- Studies addressing smart objects in domains unrelated to BIM, or those solely focusing on BIM without considering smart objects.
- Studies authored by the same author(s) and redundantly published in conferences or journals.
- Studies in languages other than English and Turkish.
- Non-peer-reviewed sources, such as blog posts and magazine publications.

Upon reviewing the reference lists of the relevant studies, an additional set of 25 studies was discovered. After eliminating any duplicate papers within this newly identified group, we assessed them according to the selection criteria, ultimately including 5 studies. Consequently, a total of 98 research papers were identified as the final set of studies.

In traditional SLR studies, the selection process often involves quality assessment questions and scoring mechanisms to determine the inclusion of relevant studies. However, due to the early stages of exploration of smart objects in the literature and the limited availability of relevant documents, this review adopts a comprehensive approach, encompassing all existing studies and refraining from applying traditional filtering criteria.

2.4. Data extraction

In this procedure, all selected studies are complied to extract information relevant to the research questions. Various features are defined, including title, author names, publication date, publication type, the name of the journal/book/conference in which the study was published, the electronic database, keywords, and the answers to the research questions. The study numbers, categorized by publication types, are presented in Fig. 2. The data obtained from the documents were then sorted, grouped and classified to facilitate the summary of results during the synthesis phase.

2.5. Data synthesis

In Appendix A, we have prepared a table indicating whether each study addresses to RQs. During data synthesis, information collected from the data extraction form and the responses to the RQs were brought together. The data are visually represented through line, box, and circle graphs. Fig. 3 illustrates the publication years of the studies, highlighting a discernible increase in research on smart objects in BIM integration from 2005 to 2023.

In accordance with the responses to RQ1 concerning the names and functions of smart objects in BIM integration stages, the studies were categorized into three main groups: (1) Pre-construction Phase, (2) Construction Phase, and (3) Post-Construction Phase. The distribution of studies across these primary categories is presented in Table 3. This classification, based on the role of smart objects for each BIM integration stage, is detailed in Section 3.1. The responses to RQ2, aimed at determining the software utilized for creating smart objects (as detailed in Section 3.2), revealed that studies predominantly employed Revit, Dynamo, and ArchiCAD for BIM integration across various project stages. The identification of commonly used data extraction tools was derived from the answers to RQ3 (covered in Section 3.3). The findings from RQ4, designed to uncover the advantages and challenges associated with the implemented processes, are consolidated and elaborated upon in the discussion section.

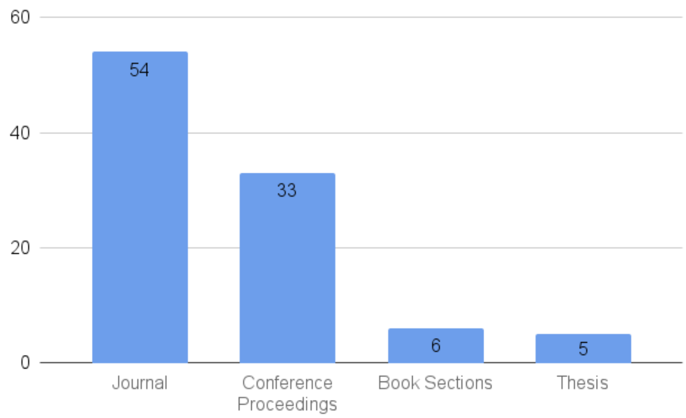

Fig. 2. Distribution of studies according to publication type

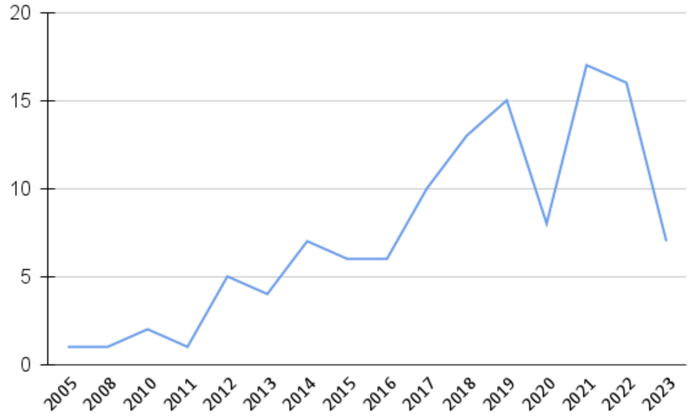

Fig. 3. Distribution of studies according to publication year

Table 3. Distribution of studies according to project phase

Phase	Study Ref No
(1) Pre-construction (Design)	[8], [9], [11], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]
(2) Construction	[3], [5], [15], [38], [41], [42], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71]
(3) Post-Construction	
Smart Buildings	[7], [11], [13], [22], [23], [24], [27], [33], [83], [84], [85], [86], [34], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99]
As-built BIM	[6], [20], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82]

3. Smart Objects in BIM Integration

In the virtual space, building components like doors, windows, walls, or floors are classified as ‘smart objects’ based on specific definitions. These definitions encompass numerical parameters such as dimensions and incorporate crucial details like environmental data and user-specific attributes [6, 19, 29]. Smart objects can be further enhanced with interactivity through sensors, enabling them to respond not only to their surroundings but also to user requests. The resulting BIM model, created from these smart objects, exhibits a highly structured nature, facilitating information segmentation for diverse stakeholders. Additionally, it is computationally lighter, occupying less memory, and offers increased ease of editing [8, 19, 20].

Despite the varied terminology used in different studies, see Fig. 4, the core essence of these objects remains constant. In this article, they are collectively referred to as “smart objects” due to their shared foundational principles. The systematic process of crafting smart objects is organized into distinct sections within this study and outlined in Fig. 5.

3.1. Smart objects in the life-cycle of a building

3.1.1. Smart objects in pre-construction (design) phase

In the design phase, architects can integrate intelligent objects into building models using BIM, fostering a transition towards design intelligence.

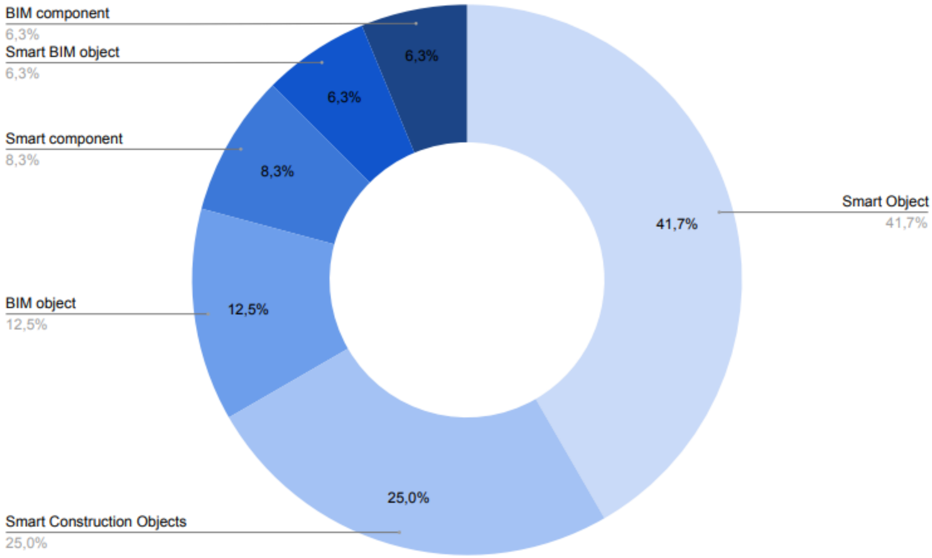

Fig. 4. Usage rates of different smart objects in studies

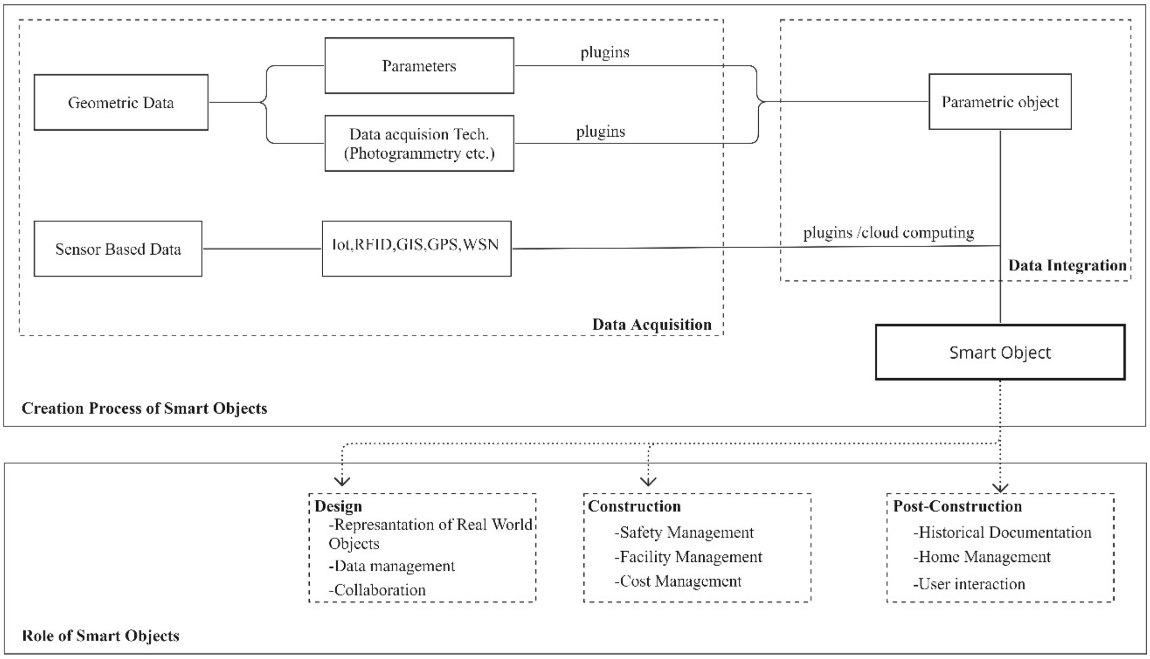

Fig. 5. Creation process and role of smart objects

There is a growing need for these systems to adopt a user-centered design approach, prioritizing interactive spaces over mere digital representation [11, 31, 32, 33]. Smart objects, equipped with specific functions, encapsulate environmental data [35] and can respond to user requests [11, 32] based on their defined properties. Designers can incorporate smart objects into building models, ranging from basic components like doors and windows to more complex design configurations such as building cores and facade elements [19, 40]. Smart objects in BIM applications are programmed with both morphological parameters and relationship parameters [21, 40, 41, 72, 83].

According to Afsari et al.'s study [22], in the case of an automatic door, standard parameters such as height, depth and width were initially modeled, followed by the addition of sensor and activator parameters. These secondary parameters, responsible for endowing the object with smart capabilities, are binary, taking values of 0 and 1. This on-off nature allows the model to respond dynamically during simulations. For instance, if the temperature parameter falls within the appropriate range, it takes the value 0; otherwise, it takes the value 1, enabling the control of the door's opening and closing in the model.

The interaction with the imitated environment through actuator parameters entails the transfer of data, reflecting real-world conditions into the BIM model. This process results in simultaneous adjustments within the model based on the acquired data. In the study by Heidari et al. [11], a task-oriented interaction approach is proposed for application in the design process. To facilitate user interaction with the virtual model created in the BIM environment, a prototype is generated, allowing users to experience it through screens. This method assesses user engagement in daily activities such as cooking and TV watching within a designed spatial context. The approach highlights the potential to improve communication between users and designers through smart objects, particularly in the development of smart environments.

Smart objects also play a crucial role in enhancing the efficiency and accuracy of code compliance checking processes. They can embed predefined rules or integrate data related to specific code requirements, automatically checking these rules during the design phase. This helps identify potential code violations early in the process [25, 28, 34]. Beyond providing real-time feedback on other design elements, smart objects can be programmed to adapt to changes in building codes. When there are updates or revisions to codes and standards, these objects can be easily modified. Their integration acknowledges the limitations associated with human input, contributing to the development of safer and more compliant built environments.

3.1.2. Smart objects in construction phase

Advanced data-driven BIM systems can be incorporated into both project management and monitoring. BIM is a comprehensive approach that covers various facets of building design and construction, including building geometry, spatial relationships, details about materials, finishes, and structural properties, as well as quantification of materials and resources required for construction [15, 44, 47, 51]. The convergence of construction and IoT technology is exploring innovative approaches for embedding BIM information within construction components. Hence, the concept of smart construction objects (SCOs) is introduced, involving the enhancement of construction resources with sensing, processing, and communication capabilities [50, 51].

Smart objects, capable of collection of diverse data, facilitate effective communication among project stakeholders throughout all stages of construction, from planning to facility management [36, 46, 96]. The potential applications of these objects have the capacity to revolutionize the construction industry by addressing persistent challenges related to safety, quality, and productivity [69]. IoT integration enables the dynamic inclusion of extensive real-time information [3], broadening the potential for automated decision-making and facilitating both horizontal and vertical collaboration for on-site operations [42, 63, 65, 68]. In this way, SCOs accurately capture information such as working crew status, supply management, inventory levels, and conditions of the working space [5, 47, 54]. This data is then made available to various parties involved in the construction process.

3.1.3. Smart objects in post-construction phase

In the post-construction phase of a building, BIM serves as a comprehensive data repository for physical information related to smart objects. This facilitates the recording of intricate details and enables the documentation and visualization of their installation locations in a 3D format. Such capabilities are advantageous for activities such as maintenance, operation and asset tracking [23, 73, 77, 78].

Smart Buildings:

Integration of technological advancements into the design of smart environments introduces a new dimension to buildings. Merging BIM with the design and management of smart buildings is feasible through the incorporation of intelligent object profiling and information exchange data [5, 23, 83]. This integrated approach empowers advanced control and optimization of smart buildings, harnessing the capabilities of intelligent objects and leveraging BIM's comprehensive data and modeling capacities [22, 33, 95].

The implementation of intelligent building systems can be achieved by either incorporating smart technologies into existing BIM objects or by creating smart object models from scratch. The key differentiation between smart objects and standard parametric BIM objects lies in the functionality of smart components, which actively engage with building users or other objects, facilitating real-time data integration [11, 32, 86].

Smart objects operate by utilizing indoor data collected through real-world sensors and facilitating simultaneous data transfer to the virtual world [7, 58, 94, 96, 100]. This data stream, coupled with the concept of a digital twin of a place, user interfaces, and web services, fosters a user-centered approach to representing virtual services and configuring smart capabilities [33, 91, 98]. Smart buildings require the integration of interactive smart objects that are capable of responding to touch/voice, remote control, motion detection, biometric recognition, or any other forms of request [11, 86, 94]. These components typically blend architectural elements with smart technologies, encompassing LCDs to sensors. The integration of smart appliances and lighting systems, automated window treatments, health monitoring devices, waste management systems and more into buildings can significantly enhance comfort levels while concurrently promoting energy efficiency, security and safety [24, 93]. In summary, real-time data integration has the potential to lead to improved sustainability, financial performance, energy management and operational efficiency in smart buildings [13, 84, 89, 91, 97, 98].

The process of implementing smart buildings unfolds as follows: initially, a digital twin of the building is generated within a model environment. Subsequently, integrated sensors embedded in smart objects facilitate the exchange of data between the physical building and its virtual counterpart [11, 22, 34]. The gathered information is stored in a cloud-based environment and disseminated to relevant smart objects based on their respective categories, facilitated by plug-ins like Dynamo [94]. Visualization within the model is finalized, and the information is transmitted to subsequent relevant objects. Additionally, mobile devices (such as phones and screens) can control smart objects through sensors, enhancing user interaction. In this context, architectural components serve as interaction interfaces, with smart objects assuming the role of these architectural constituents [33, 85].

Artificial intelligence is taking smart environment technology to a whole new dimension. AI simulation models have the capacity to enhance the functionality of intelligent buildings, improve occupant comfort, and significantly reduce energy consumption through better control, increased reliability and automation [97]. Intelligence-enabling technologies, such as big data analytics, can be integrated into digital twin ecosystem to improve the efficiency of smart construction process and environments by automating motion data collection [91]. AI has the capability to construct a behavioral model using data gathered from various sources, including microcontrollers, intelligent control systems, and sensors. And, specific tasks can be automated according to user preferences, employing smart BIM objects powered by AI. For example, a ceiling designed as a smart object can be customized for different purposes using AI [98]. The integration of sensors to detect environmental changes like temperature, humidity, light levels, and motion not only promotes energy efficiency but also refines the overall user experience.

As-Built BIM:

The term "as-built BIM" refers to the documentation of existing structures using BIM. This encompasses both a depiction of the structure as it was constructed ('as-built' representation) and its current state ('as-is' representation) [101]. BIM's ability to gather data is valuable for improving preservation efforts [77, 78] and simplifying documentation and analysis of existing structures [101]. A comprehensive digital model, containing extensive information and incorporating data collected during surveys, enables the examination of morphotypological changes in buildings without the need for additional surveys [73, 20]. In short, BIM is a methodology that involves the digitalization process of both existing buildings and historical structures (HBIM). Notably, many studies on integrating smart objects have focused on historical buildings.

HBIM is tailored specifically for managing historic buildings, while BIM represents a more comprehensive process that employs digital models as its primary language [4]. Heritage buildings, characterized by diverse historical layers, additions, demolitions, and changes in use over time, may not readily align with standardization procedures, which are a strength of BIM [6].

The integration of semantic content and meta-information within smart objects significantly contributes to the preservation, understanding, and accessibility of cultural heritage, fostering a deeper connection between past and present generations [73, 20]. This involves associating meaningful data, such as narratives and context-specific details, with smart objects, enriching their representations and enhancing their interactions within the virtual environment. By embedding relevant meta-information, such as historical context, cultural significance, and conservation status, into the smart object models, a comprehensive understanding of heritage structures is achieved. These semantic and meta-information elements also support better decision-making during preservation, restoration, and future planning efforts. This approach ensures that smart object models not only represent the physical characteristics of cultural heritage structures but also serve as repositories of contextual knowledge and insights, enriching the overall experience for both viewers and researchers. HBIM functions as an advanced library of parametric and smart objects derived from historical architectural data [72, 76, 80]. The 3D model is converted into smart objects organized in libraries, then mapped onto survey data for a comprehensive representation of historic structures [72, 73, 80].

When existing buildings are recreated in the digital environment, smart BIM objects, similar to those used in the design of new buildings, represent actual elements of the structure. The acquisition and preparation of these components involve characterizing three types of knowledge: physical shapes, specific identities, and relationships among various elements [72, 76, 80]. This acquired data serves as a foundation to incorporate specific information about the smart object, including its connection with other components, material specifications, and joint details.

The as-built BIM process for existing or historical buildings comprises three primary phases. Initially, data collection incorporates several techniques such as Terrestrial Laser Scanning (TLS) and digital photogrammetry to minimize errors [6, 73, 77, 80]. In the second phase, data processing involves tasks such as noise cleaning, point re-sampling, and point cloud registration to enhance accuracy [72, 74]. Finally, the modeling phase encompasses polygonal surface meshing and texturing, along with the establishment of a parametric and smart object library using basic geometric shapes and predetermined parameters to accurately build the elements [6, 77]. Garagnani et al. note that the core intelligence within smart objects originates from methods like photogrammetry or TLS, essential for their creation. These objects are also designed as 'self-aware,' programmed with specific rules for interaction. For instance, a historical column, when modeled as a smart object, undergoes division into sections (such as header, body, and base) and integrates point cloud or laser scan outputs, or is modeled anew from this data. Parametric features are added during modeling, defining interactions with other objects. The 3D reproduction of buildings enables the monitoring and management of existing or historical structures through a real-time visualization system, providing control and tracking capabilities throughout the building's lifecycle [73].

3.2. Sofware

Several BIM software options, such as Revit and ArchiCAD, are accessible for professional use in office applications and for academic purposes among students [103]. Additionally, tools for parametric design, generating algorithm and visual programming such as Dynamo and Grasshopper, plugins for generative design like Firefly and Greenspider, Application Programming Interface (API) such as Rhino.Inside, and technologies for data exchange and interoperability (IFC exporter) are commonly employed to enhance functionality. Fig. 6 provides an overview of the software used for smart objects, with Revit emerging as the primary choice for creating such objects in the majority of cases.

The availability of modeling software for creating and specifying the requirements of smart objects introduces a new dimension to building model management. It enables rapid modeling, immediate feedback, and validation of design integrity through a library of compatible and reusable smart objects that can autonomously provide and request data for proper functionality. In the development of BIM objects, parameters can be entered manually or automatically [60]. Research findings suggest that parameters are generally assigned prior to the modeling phase in BIM, offering flexibility for modifications throughout the project as required [6, 80, 81]. Furthermore, taking into account factors like model size, complexity, the number of elements, and angles of element connections, utilizing parameters for smart model creation facilitates a shorter and more streamlined process compared to conventional methods [105].

Object-oriented parametric modeling forms the foundation of BIM, represented by configurations of Revit families. Using Revit's built-in scripting capabilities, technical guide instructions are systematically applied to the design [28, 74]. Incorporating new parameters enhances the information content, enabling the creation of data-rich objects. When specific parameters are defined for smart objects in the BIM environment, it becomes possible to develop interactive 3D models that interface with artificial intelligence (AI) recognition systems. This integration improves model capabilities for intelligent recognition and interaction with the objects [25].

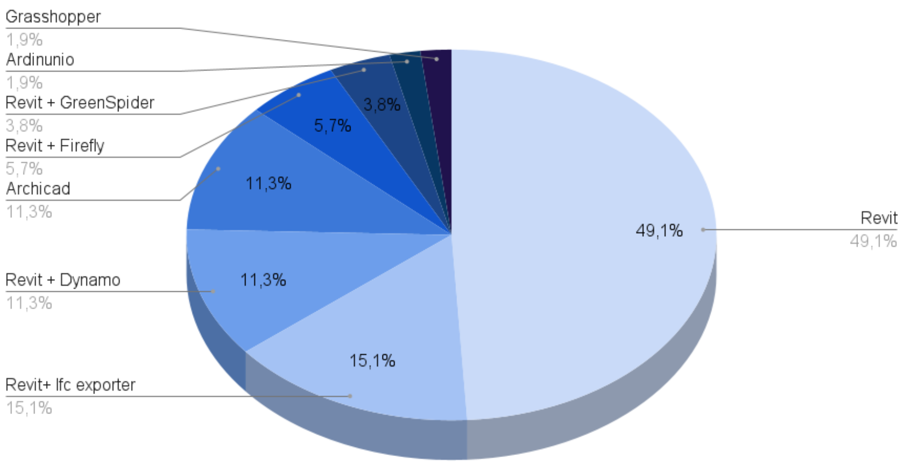

Fig. 6. Distribution of software and plugins

However, modeling software like Revit has constraints on inherent family-specific parameters, offering limited data accessibility [21]. Similarly, programs like ArchiCAD offer limited access to model data, incorporating a predetermined set of "Global-Variables" for preferences without customization or expansion options [21].

While BIM modeling excels in building information and visualization, it lacks the inherent ability to integrate information about the immediate environment [42, 55]. This limitation is often addressed through plugins, playing a crucial role in enhancing connectivity and interoperability for smart objects within the system. Dynamo, commonly employed as a plugin with Revit, acts as a tool to incorporate family-specific procedural information into the BIM environment [7, 26, 42]. It facilitates the creation of smart objects by enabling precise transformation of object parameters. Also, this plugin enhances the flexibility and extensibility of smart objects in design and workflow management, fostering greater adaptability and versatility [19, 96]. Moreover, Dynamo with Revit allows the emergence of experimental smart components [42, 55]. In a study by Chiens et al., smart objects for a kinetic shading system were produced using the Raindrops package in Dynamo [26]. According to Chang et al. [42], Dynamo aids in management decisions by integrating sensor data and updating visualized information in the BIM environment [5, 22, 42]. Serving as a link between the IoT platform and the building model, Dynamo executes scripts directly in Revit, enabling the monitoring of specific areas for measured parameters [96]. The integration of IoT and BIM is not limited to the Dynamo plugin; some studies also utilize different plugins like API for this purpose [23, 58].

3.3. Data acquisition

Incorporating BIM into cloud computing and IoT-based systems significantly improves communication and human supervision. This multi-layered process is tailored for specific purposes, enhancing collaboration and project efficiency.

Data acquisition technologies in BIM refer to the methods and tools used to collect, capture, and input data into the digital models of buildings or infrastructure. Some common data acquisition technologies/systems include IoT, RFID (Radio-Frequency Identification), WSN (Wireless Sensor Networks), GIS (Geographic Information System), GPS (Global Positioning System), digital photogrammetry, TLS, and LIDAR (Laser Imaging Detection and Ranging) [46, 91]. The data collected by smart objects enables them to make informed decisions, trigger specific responses, or communicate with other devices [11, 32, 33]. Fig. 7 displays the distribution of data acquisition tools found in documents.

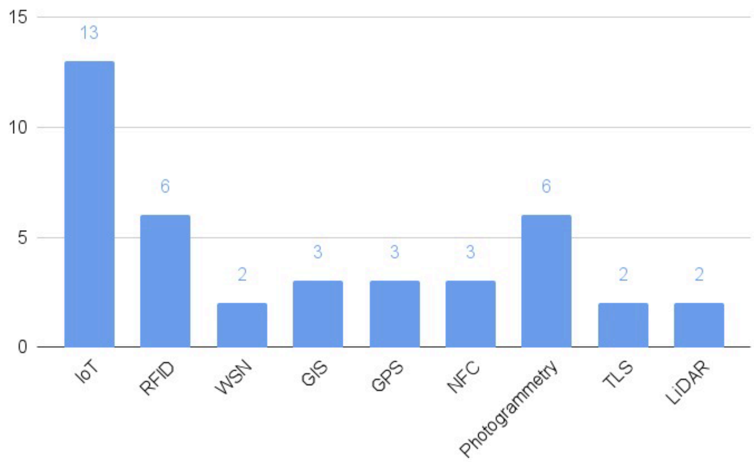

Fig. 7. Distribution of data acquisition tools

In the BIM-created model, data gathering facilitates a comprehensive repository of information for analysis. Once the virtual 3D space and sensor locations are set, plugins like Firefly are utilized to incorporate real environmental data into the virtual environment. This process enables realistic simulations and thorough analysis [11, 26, 42]. Firefly plays a crucial role as a plugin by facilitating connections between BIM-based parametric design software like Dynamo, sensor microcontrollers like Arduino, and various input/output devices such as webcams and mobile phones.

3.3.1. Sensors

Various types of sensors are utilized to enable spatial interaction with smart objects, each having unique range properties. For example, an infrared motion sensor scans a circular area, while a temperature sensor covers a spherical area [23]. Additionally, virtual sensors observe the state of BIM objects, capturing geometric, semantic, and building element data, and provide information when changes occur [58, 100].

The integration of the BIM model with sensor data is achieved through plugins like Dynamo for visual programming [7, 26, 74, 96]. Combining Revit, Dynamo and Arduino platforms enables efficient data visualization. The process begins by creating a smart object model in Revit. Arduino acts as a bridge, facilitating communication between sensors and the virtual environment by processing data from sensors and transmitting it. Dynamo accepts data inputs from Arduino, automatically generating visual representations within the design software. While microprocessors, often embedded in Arduino or other devices, analyze collected data and send commands to actuators for responsive actions, Dynamo serves as a powerful tool for integrating this functionality into the BIM software. During the data exchange between the user, the physical environment and the virtual environment, two different types of interactions are established: direct interaction (like pressing a button or toggling a switch) and indirect interaction (involving gestures and voice commands) [11, 33]. To achieve these interactions, smart objects need to be augmented with parameters explicitly tailored for sensors and actuators.

3.3.2. Internet of Things (IoT)

The sensor-actuator paradigm has evolved from conventional wired connections to the IoT, fostering the creation of interconnected objects that form a network capable of autonomous task execution without human intervention [22, 42, 96]. Coined in the 20th century to describe the application of RFID technology [15, 102], the term ‘Internet of Things’ refers to a network of sensor-integrated smart objects communicating with virtual systems, enabling autonomous decision-making and real-time monitoring. IoT functions as a platform facilitating the connection between smart objects and virtual back-end systems, reducing the reliance on human intervention and minimizing the risk of errors in the AEC industry [15, 42, 46, 94, 96, 104].

Integrating BIM with data from IoT devices is a powerful approach with many applications, enhancing both construction and operational efficiencies [47, 62, 96]. Within this framework, an IoT system in BIM collects diverse data types—temperature, humidity, air pressure, emissions, load, motion, distance, deformation, and energy consumption [5, 36, 96]. This integrated system proves valuable across various aspects of project management, encompassing cost, schedule, inventory, quality control, safety, and production management, especially in the precast industry [7, 10, 46].

3.3.3. Other systems and technologies

Physical technologies, including RFID, GIS, GPS and NFC, are efficiently employed for data collection, monitoring, and analysis [22, 46, 78]. They significantly enhance the automation process by providing precise and comprehensive data insights.

The collaborative utilization of BIM, GIS, and smart objects can enable a holistic understanding of the built environment, promoting effective monitoring and decision-making in urban settings [27, 100]. Infrastructure elements embedded with sensors enable predictive maintenance and proactive responses to various issues, such as equipment malfunctions and structural degradation. Integration with GPS technology provides spatial context and real-world coordinates to BIM and smart objects. For instance, construction materials and equipment embedded with GPS sensors and linked to the BIM model can be tracked in real time, optimizing resource allocation and enhancing construction site management.

Image-based (photogrammetry) and video-based (TLS and LIDAR) data collection methods are widely used in BIM for existing buildings and HBIM studies to achieve accurate and comprehensive data capture [73, 77, 80]. These technologies play a crucial role in preserving and documenting existing and historical structures, with a focus on geometric data collection [72, 73, 81]. The collected data is transformed into point clouds using programs like Agisoft Metashape and ReCap. After exporting the point cloud in a suitable format (such as .ifc or .obj), it is imported into BIM applications. Throughout the data processing, plugins like GreenSpider and Faro are utilized to convert 3D meshes into smart objects. In the studies carried out, the priority is to provide more information about architectural elements while minimizing data loss, showing greater success compared to manual data collection methods.

4. Discussion

The findings derived from addressing the research questions can be summarized as follows:

RQ1: Smart objects find application across all project phases, adopting different names depending on the phase, such as smart components, smart construction objects, and smart BIM objects. Regardless of diverse terminology, these smart objects essentially serve the same purpose: acting as digital twins of existing or planned physical objects and engaging with their environment. The methods of interaction and attributes of these objects may display variability in relation to their environment.

RQ2: In the studies under examination, smart objects are modeled using various software programs, with Revit being the most frequently employed, followed by ArchiCAD and Rhino. Dynamo stands out as the most prevalent plugin. Moreover, Arduino plays a key role as a platform for communication and sensor integration with these intelligent objects.

RQ3: The studies employ various data acquisition methods, including sensors, IoT, RFID, GIS, GPS, WSN, and NFC. Visual methods like photogrammetry and TLS are utilized for existing and historical structures. Smart objects communicate through cloud-based, IoT-based, or other system-based environments, and interaction can be enhanced through mobile devices or screens.

RQ4: Smart objects modeling is conducted in 38 studies (around 40 percent of all papers), primarily on a building component scale. These models often represent digital twins of components like windows, walls, or doors, while some studies focus on building-scale information models. The majority of HBIM studies feature case studies, with a strong emphasis on preservation and documentation. Photogrammetry of laser scanning is commonly used for data acquisition, and Revit as the most-used modeling tool.

Additionally, case studies explore applications in construction and project management. In some of these studies, smart object models are utilized by exporting them in IFC format, resulting in data loss and posing challenges in integrating collected data back into the BIM system. In the ISO19650 and BS1192 standards for BIM management plans, we observed a lack of provisions for data acquisition technologies or parameter requirements specific to smart objects. These contemporary standards primarily address the technical aspects of objects, such as the Level of Development (LOD). Our analysis of existing studies indicates an absence of standards or guidelines outlining the creation stages of smart objects and specifying the requisite information they should encompass.

Case studies related to design phase were limited, testing smart object functions through simulations. The incorporation of virtual sensors into smart objects was not observed in these studies. Only a couple of studies addressed smart objects within virtual environments, such as Virtual Reality (VR) and Augmented Reality (AR).

5. Conclusion

The relationship between BIM and Smart objects embodies a dynamic synergy at the forefront of modern construction and design. BIM, serving as a multidimensional digital representation of a building's physical and functional characteristics, forms the foundational framework for managing information throughout the entire project life cycle. Smart objects, imbued with sensors and data-driven intelligence, enrich this framework by enabling real-time interaction and data exchange. This interconnectedness fosters enhanced collaboration among stakeholders, facilitates informed decision-making, and drives efficiency across planning, construction, operation, maintenance, and preservation phases. Smart object profiling enables enhanced control and optimization of smart environments and leads to an improved communication between users and designers.

As a result of the examined documents, smart objects are divided into three categories according to their use in different project phases: design, construction and post-construction. While the fundamental utilization of smart objects within these respective stages retains its inherent purpose, discernible variations in certain aspects may arise. Given that smart objects are connected to diverse concepts and terms within BIM landscape, a keyword network map was created in Fig. 8. This map could assist researchers in organizing information and planning their contribution to the field.

In this paper, we presented the characteristics, methods, tools, and limitations related to integrating BIM with smart objects. Here are the recommendations for future studies based on our findings:

(1) The specific guidelines and standards on how to model and document smart objects will help ensure the accurate incorporation of necessary data within the BIM model and promote efficient collaboration among various stakeholders. Updating relevant instructions and standards regarding the design and integration process of smart objects will contribute to their adaptability and flexibility.

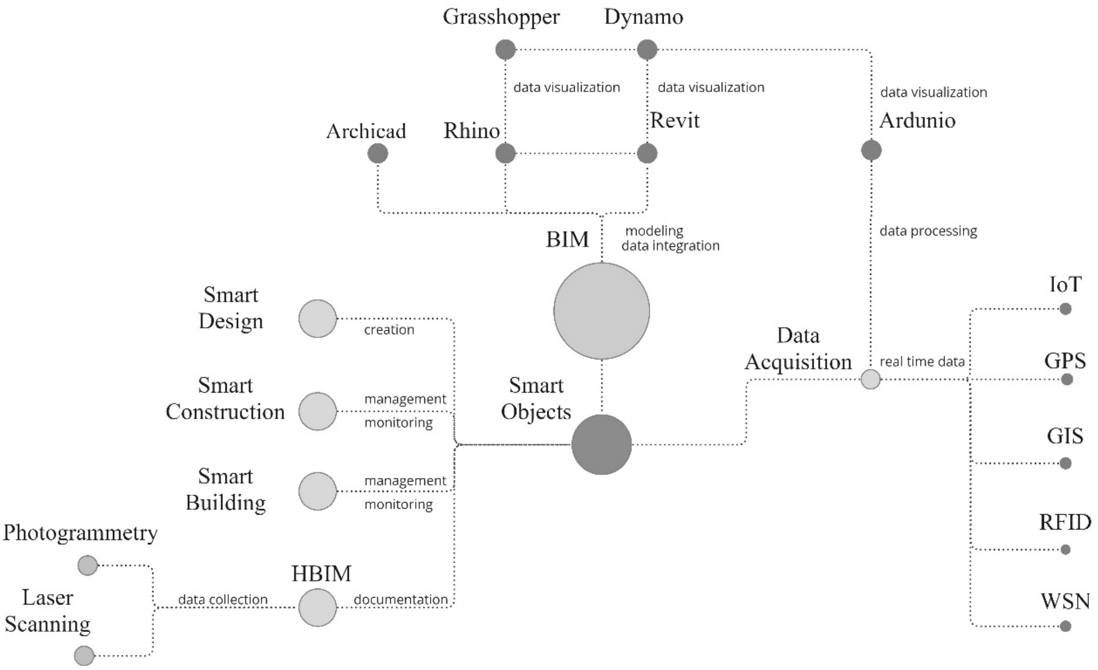

Fig. 8. Keyword network map

(2) In many studies, the terms "smart object" and "parametric object" are often used interchangeably without clear definitions. Parametric objects are components controlled by adjustable parameters, enabling quick design changes while maintaining consistency. Smart objects, a more advanced version, are data-rich components, containing both graphical and non-graphical information, enhancing collaboration and decision-making throughout the building life cycle. It's crucial to consider this distinction and contextually clarify object qualities.

(3) A predominant trend in existing 'smart object' studies is to concentrate on specific project stages such as design, construction, or post-construction. This approach constrains the sustainable applicability of smart objects throughout all project phases. Projects that encompass the complete life cycle, from creation to management, of smart objects would provide a holistic understanding of their functionality. Future research should consider examining the behaviors of smart objects comprehensively within a unified study.

(4) In the Post-Construction phase, effective data acquisition plays a crucial role in HBIM. However, studies reveal a common practice of transferring acquired data into the digital model in a basic form, typically as meshes. This approach hinders the efficacy of smart objects and compromises their long-term viability. Future research efforts could involve the development of robust plugins or innovative design packages using Dynamo or Python code to establish automated procedures for the proficient modeling of heritage buildings.

(5) Research findings suggest that, conventionally, smart objects are individually modeled for each project. Establishing libraries that contain pre-designed and predefined smart objects presents a more systematic approach for future projects, requiring less energy compared to creating smart objects anew for every project.

In conclusion, this comprehensive review of smart objects in BIM highlights their potential for enhancing collaboration, efficiency, and data-driven decision-making across construction and design phases. As automation technology evolves, the strategic integration and continuous refinement of smart objects promise to play an important role in BIM practices.

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Author Contributions

Kubra Yilmaz Senel: Conceptualization, Methodology, Investigation, Writing - Original Draft, Visualization; Asli Cekmis: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

Not applicable.

Conflict of Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] Sabol L (2008) Building information modeling & facility management. In: IFMA World Workplace. Dallas, USA.

[2] Nederveen GA, Tolman F (1992) Modelling multiple views on buildings. Automation in Construction 1: 215-224.

[3] Li CZ, Zhong RY, Xue F, Xu G, Chen K, Huang GG, Shen GQ (2017) Integrating rfid and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. Journal of Cleaner Production 165:1048-1062.

[4] Eastman C, Teicholz P, Sacks R, and Liston K (2011) BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors. John Wiley Sons Publishing.

[5] Honcharenko T, Kyivska K, Serpinska O, Savenko V, Kysliuk D, Orlyk Y (2021) Digital transformation of the construction design based on the building information modeling and internet of things. In:1nd International Workshop on Information Technologies: Theoretical and Applied Problems.Ternopil, Ukraine.

[6] Pocobelli DP, Boehm J, Bryan P, Still J, Grau-Bove J (2018) Bim for heritage science: A review. Heritage Science 6(12).

[7] Valinejadshoubi M, Moselhi O, Bagchi A (2022) Integrating BIM into sensor-based facilities management operations. Journal of Facilities Management 20:385-400.

[8] Ibrahim M, Krawczyk R (2003) The level of knowledge of cad objects within the building information model. In: Proceedings of the 23th Annual Conference of the Association for Computer-Aided Design in Architecture (ACADIA).

[9] Halfawy M, Froese T (2005) Building integrated architecture/engineering/construction systems using smart objects: Methodology and implementation. Journal of Computing in Civil Engineering 19:172-181.

[10] Sawhney A, Maheswari JU (2013) Design coordination using cloud- based smart building element models. International Journal of Computer Information Systems and Industrial Management Applications 5:445-453.

[11] Heidari M, Allameh E, Vries BD, Timmermans H, Jessurun J, Mozaffar F (2014) Smart-BIM virtual prototype implementation. Automation in Construction 39:134-144.

[12] Lopez TS, Ranasinghe DC, Harrison M, McFarlane D (2012) Using smart objects to build the internet of things. IEEE Internet Computing.

[13] Kortuem G, Alford D, Ball L, Busby J, Davies N, Efstratiou C, Finney J, White M, Kinder-Kurlanda K (2007) Sensor networks or smart artifacts? An exploration of organizational issues of an industrial health and safety monitoring system. In: Lecture Notes in Computer Science.

[14] Mattern F (2003) From smart devices to smart everyday objects. Ubiquitous Computing: Scenarios for an Informatized World and E-Merging Media. Springer Publishing.

[15] Niu Y, Anumba C, Lu W (2019) Taxonomy and deployment framework for emerging pervasive technologies in construction projects. Journal of Construction Engineering and Management 145 (5).

[16] Kitchenham CS (2012) Systematic review in software engineering: Where we are and where we should be going. In: Proceedings of the 2nd International Workshop on Evidential Assessment of Software Technologies. New York, USA.

[17] Siddaway A (2014) What is a systematic literature review and how do i do one. University of Stirling, 1(1):1-13.

[18] Muller MF, Esmanioto F, Huber N, Loures ER, Junior OC (2019) A systematic literature review of interoperability in the green building information modeling life-cycle. Journal of cleaner production, 223:397-412.

[19] Chen S, Lok K, Jeng T (2016) Smart BIM object for design intelligence. In: The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA).

[20] Garagnani S (2013) Building information modeling and real world knowledge: A methodological approach to accurate semantic documentation for the built environment. In: Digital Heritage International Congress.

[21] Kirchner JJ, Huhnt WW (2021) A formal approach for interfaces and requirements of smart objects in building models. In: Procedings of the Conference CIB W78 2021. Luxembourg.

[22] Afsari K, Florez L, Maneke E, and Afkhamiaghda M (2019) An experimental investigation of the integration of smart building components with building information model (BIM). In: International Association for Automation and Robotics in Construction (IAARC). Banff, Canada.

[23] Zhang J, Seet BC, Lie TT (2015) Building information modelling for smart built environments. Buildings 5:100-115.

[24] Vries BD, Allameh E, Jozam MH (2012) Smart-BIM (Building Information Modeling). Gerontechnology 11(2).
[25] Sun H, Kim I (2022) Applying AI technology to recognize BIM objects and visible properties for achieving automated code compliance checking. Journal of Civil Engineering and Management 28:497-508.
[26] Chien S, Choo S, Schnabel MA, Nakapan W (2016) Adaptive building facade optimisation an integrated green-bim approach. The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). Hong Kong, China.
[27] Dolas C, Dieckmann A, and Russell P (2013) Building your own urban tool kit utilizing parametric bim components as smart early design tools for large-scale urban planning. In: Proceedings of eCAADe Conference. Delft, Netherlands.
[28] Patlakas P, Livingstone A, Hairstans R, Neighbour G (2018) Automatic code compliance with multi-dimensional data fitting in a bim context. Advanced Engineering Informatics 38:216-231.
[29] Li N, Li Q, Liu YS, Lu W, Wang W (2020) BIM-seek++: Retrieving BIM components using similarity measurement of attributes. Computers in Industry 116 (4).
[30] Laali A, Nourzad SY, Faghihi V (2022) Optimizing sustainability of infrastructure projects through the integration of building information modeling and envision rating system at the design stage. Sustainable Cities and Society 84(9).
[31] Barazi A (2018) Real-time integration of ieq with BIM user-centered approach. Aalto University.
[32] Jozam MH, Allameh E, Vries BD, Timmermans H, Masoud M (2012) VR-smart home prototyping of a user centered design system. Lecture Notes in Computer Science 7469: 107-118.
[33] Dasgupta A, Handosa M, Manuel M, Gracanin D, (2019) A user-centric design framework for smart built environments: A mixed reality perspective. Lecture Notes in Computer Science 11587: 124-143. Springer Verlag.
[34] Doukari O, Seck B, Greenwood D, Feng H, Kassem M (2022) Towards an interoperable approach for modelling and managing smart building data: The case of the smart building demonstrator. Buildings 12: 3.
[35] Bueno C, Fabricio MM (2017) Methodological discussion of insertion and exportation of lca data embedded in bim elements. In: WIT Transactions on the Built Environment. United Kingdom.
[36] Scheffer M, König M, Engelmann T, Ciribini A (2018) Evaluation of open data models for the exchange of sensor data in cognitive building. In: 2018 Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2018.
[37] Gheisari M, Williams G, Walker BN, Irizarry J (2014) Locating building components in a facility using augmented reality vs. paper-based methods: A user-centered experimental comparison. In: Computing In Civil And Building Engineering pp 850-857.
[38] Tang S, Shelden DR, Eastman CM, Bozorgi PP, Gao X (2019) A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. Automation in Construction 101: 127-139. Elsevier B.V.5.
[39] Ruiz-Zafra A, Benghazi K, Noguera M (2022) Ifc+: Towards the integration of IoT into early stages of building design. Automation in Construction 136. Elsevier B.V., 4.
[40] Kaçmaz Ş (2019) Parametrik tasarim ve BIM. Yapı Bilgi Modelleme 1:3-9.
[41] Singh MM, Sawhney A, Borrmann A (2015) Modular coordination and BIM: Development of rule based smart building components. Procedia Engineering 123: 519-527. Elsevier.
[42] Chang KM, Dzeng RJ, Wu YJ (2018) An automated IoT visualization BIM platform for decision support in facilities management. Applied Sciences 8:7.
[43] Chung C (2018) BIM smart objects in a knowledge-enabled cloud-based platform. The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). Hong Kong, China.
[44] Parsa M (2021) Smart BIM objects for intelligent modular construction. University of Minho.
[45] Zhu A, Pauwels P, Vries BD (2021) Smart component-oriented method of construction robot coordination for prefabricated housing. Automation in Construction 129(9).
[46] Banerjee A, Nayaka RR (2021) A comprehensive overview on BIM-integrated cyber physical system architectures and practices in the architecture, engineering and construction industry. Construction Innovation.
[47] Zhai Y, Chen K, Zhou J, Cao J, Lyu Z, Jin X, Shen G, Lu W, Huang GQ (2019) An internet of things-enabled BIM platform for modular integrated

construction: A case study in Hong Kong. Advanced Engineering Informatics 42:10.
[48] Li X, Shen GQ, Wu P, Xue F, Chi H, Li CZ (2019) Developing a conceptual framework of smart work packaging for constraints management in prefabrication housing production. Advanced Engineering Informatics 42.
[49] Kang K, Besklubova S, Dai Y, Zhong RY (2022) Building demolition waste management through smart BIM: A case study in Hong Kong. Waste Management 143:69-83.
[50] Niu Y, Lu W, Liu D (2017) The application scenarios of smart construction objects (scos) in construction. In: Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate.
[51] Niu Y (2017) Smart construction objects. Journal of Computing in Civil Engineering 30: 130-138.
[52] Giovanardi M, Trane M (2021) Smart construction object. International Journal of Architecture, Art and Design 10:84-91.
[53] Singh MM, Sawhney A, Borrmann A (2015) Rule based building components for modular coordination. Creative Construction Conference. Krakow, Poland.
[54] Ghosh A, Edwards DJ, Hosseini MR (2021). Patterns and trends in internet of things (IoT) research: future applications in the construction industry. Engineering, Construction and Architectural Management 28:457-481.
[55] Tan Y, Li G, Cai R, Ma J, Wang M (2022) Mapping and modelling defect data from uav captured images to BIM for building external wall inspection. Automation in Construction 139.
[56] Lu W, Li X, Xue F, Zhao R, Wu L, Yeh A (2021) Exploring smart construction objects as blockchain oracles in construction supply chain management. Automation in Construction 129.
[57] Fernandez M, Renukappa S, Suresh S (2019) Evaluating critical success factors for implementing smart devices in the construction industry: An empirical study in the dominican republic. Engineering, Construction and Architectural Management 26:1625-1640.
[58] Kazado D, Kavgic M, Eskicioglu R (2019) Integrating building information modeling (BIM) and sensor technology for facility management. Journal of Information Technology in Construction (ITcon) 441-458.
[59] Zhu A, Pauwels P, Vries BD (2023) Component-based robot prefabricated construction simulation using ifc-based building information models. Automation in Construction 152.
[60] Moskaliuk L (2018) Benchmark of availability of BIM-objects for construction products. Oulu University of Applied Sciences.
[61] Getuli V, Capone P, Bruttini A, Sorbi T (2022) A smart objects library for bim-based construction site and emergency management to support mobile VR safety training experiences. Construction Innovation 22(6):504-530.
[62] Li CZ, Xue F, Li X, Hong J, Shen GQ (2018) An internet of things-enabled BIM platform for on-site assembly services in prefabricated construction. Automation in Construction 89:146-161.
[63] Niu Y, Lu W, Liu D, Chen K, Xue F (2017) A smart construction object (sco)-enabled proactive data management system for construction equipment management. In: Proceedings of Computing in Civil Engineering (ASCE 2017).
[64] Niu Y, Lu W, Xue F, Liu D, Chen K, Fang D, Anumba C (2019) Towards the “third wave”: An sco-enabled occupational health and safety management system for construction. Safety Science 111:213-223.
[65] Li X, Shen GQ, Wu P, Fan H, Wu H, Teng,Y (2018) Rbl-php: Simulation of lean construction and information technologies for prefabrication housing production. Journal of Management in Engineering 34(3).
[66] Liu Z, Jiang L, Osmani M, Demian P (2019) Building information management (BIM) and blockchain (BC) for sustainable building design information management framework. Electronics 8(7).
[67] Panteli C, Kylili A, Fokaides P (2020) Building information modelling applications in smart buildings: From design to commissioning and beyond a critical review. Journal of Cleaner Production 265(8): 121766.
[68] Mannino A, Dejaco MC, Cecconi FR (2021) Building information modelling and internet of things integration for facility management-literature review and future needs. Applied Sciences (Switzerland).
[69] Pan Y, Chen J, Fu Y, Lu W (2023) Integrating smart construction objects and augmented reality for onsite assembly of modular construction. In: European Conference of Computing Construction.
[70] Zhu A (2023) A robotic construction simulation platform for light-weight prefabricated structures. Eindhoven University of Technology.

[71] Singh V, Sawhney M, Sharma A (2017) Utilising building component data from BIM for formwork planning. Construction Economics and Building 17:20-36.
[72] Garagnani S (2018) Digital renovation: BIM for the built environment. New Frontiers of Construction Management Workshop 09:128-135.
[73] Barrile V, Bernardo E, Bilotta G (2022) An experimental HBIM processing: Innovative tool for 3D model reconstruction of morpho-typological phases for the cultural heritage. Remote Sensing 14.
[74] Pocobelli DP, Melinis A, Crabb N, Grau-Bov´e J (2022) Using building information modelling to map the composition of glass panes in a historic house. Digital Applications in Archaeology and Cultural Heritage 26.
[75] Abd N (2023) Smart monitoring solution through internet of things utilization to achieve resilient preservation. Ain Shams Engineering Journal 14.
[76] Pocobelli DP (2021) Heritage building information model (BIM) for scientific data.
[77] Argiolas R, Bagnolo V, Cera S, Sanna G (2022) Analytical representation of architectural built heritage: A sketch-to-BIM approach. International Society for Photogrammetry and Remote Sensing 46:33-40.
[78] Garagnani S, Mingucci R, Luciani SC (2012) Collaborative design for existing architecture: The building information modeling as a frontier for coordinated process. Sigradi 2012. Uruguay.
[79] Garagnani S (2012) Semantic building information modeling and high definition surveys for cultural heritage sites. Disegnarecon 5:297-302.
[80] Scianna A, Gaglio GF, Guardia M (2018) BIM modelling of ancient buildings. Progress in Cultural Heritage: Documentation, Preservation, and Protection pp 344-355. Springer International Publishing.
[81] Barrile V, Fotia A (2022) A proposal of a 3D segmentation tool for hbim management. Applied Geomatics 14:197-209.
[82] Li X, Shen GQ, Wu P, Yue T (2019) Integrating building information modeling and prefabrication housing production. Automation in Construction 100:46-60.
[83] Volk R, Stengel J, Schultmann F (2014) Building information modeling (BIM) for existing buildings-literature review and future needs. Automation in Construction 38:109-127.
[84] Fang T, Zhao Y, Gong J, Wang F, Yang J (2021) Investigation on maintenance technology of large-scale public venues based on bim technology. Sustainability 13.
[85] Fadakari H (2014) Evaluation of the application of building information modeling technology in intelligent architecture realization. European Online Journal of Natural and Social Sciences 3(4):634-646.
[86] Louis J, Rashid K (2018) Utilizing building information models as operating systems for smart homes. Proceedings of the Human-Habitat for Health (H3): Human-Habitat Multimodal Interaction for Promoting Health and Well-Being in the Internet of Things era-20th ACM International Conference on Multimodal Interaction.
[87] Goldman G, Zarzycki A (2015) Smart Buildings/Smart(er) Designers: BIM and the Creative Design Process. In: BIM in Current and Future Practice pp 1-16.
[88] Gracanin D, Eltoweissy M, Cheng L, and Tasooji R (2018) Reconfigurable spaces and places in smart built environments: A service centric approach. In: Communications in Computer and Information A service infrastructure.
[89] Pourzolfaghar Z, Helfert M (2017) Integration of Buildings Information with Live Data from IoT Devices. In: Connected Environments for the Internet of Things: Challenges and Solutions pp 169-185.
[90] Fratu M, Cirstolovean L (2017) Information modelling for energy efficiency in intelligent buildings. Proceedings-2017 International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2017 and 2017 Intl Aegean Conference on Electrical Machines and Power. Institute of Electrical and Electronics Engineers Inc.
[91] Sepasgozar S (2021) Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. Buildings 11(151).
[92] Kuzina O (2019) Conception of the operational information model of smart city control system. In: E3S Web of Conferences.
[93] Handosa M, Elmongui HG, Gracanin D (2017). A service infrastructure for human-centered IoT-based smart built environments. In: International Conference on Designing and Evaluating

Distributed, Ambient and Pervasive Interactions. Springer International Publishing.
[94] Colace F, Guida CG, Gupta B, Lorusso A, Marongiu F, Santaniello D (2023) A BIM-based approach for decision support system in smart buildings. In: Lecture Notes in Computer Science. Springer International Publishing.
[95] Costa AA, Lopes PM, Antunes A, Cabral I, Grilo A, Rodrigues FM (2015) 3I buildings: Intelligent, interactive and immersive buildings. In: Procedia Engineering.
[96] Desogus G, Quaquero E, Rubiu G, Gatto G, Perra C (2021) BIM and IoT sensors integration: A framework for consumption and indoor conditions data monitoring of existing buildings. Sustainability 13(4).
[97] Almusaed A, Yitmen I, Almssad A (2023) Enhancing smart home design with ai models: A case study of living spaces implementation review. Energies 16(3).
[98] Saher N (2023) Smart homes and future AI based models. International Journal of Innovations in Science Technology 5:143-159.
[99] Gracanin D, Matkovic K, Wheeler J (2016) An approach to modeling internet of things based smart built environments. In: Proceedings-Winter Simulation Conference.
[100] Isikdag U (2015) BIM and IoT: A synopsis from GIS perspective. International Society for Photogrammetry and Remote Sensing 40: 33-38.
[101] Dore C, Murphy M (2017) Current state of the art historic building information modelling. In: International Society for Photogrammetry and Remote Sensing 42:185-192.
[102] Zhou JX, Shen GQ, Yoon SH, Jin X (2021) Customization of on-site assembly services by integrating the internet of things and BIM technologies in modular integrated construction. Automation in Construction 126.
[103] Kalfa MS (2018) Building information modeling (BIM) systems and their applications in Turkey. In: Journal of Construction Engineering, Management & Innovation 1:55-66.
[104] Gregus M, Lokshina IV, Wade LT (2019) Application of integrated building information modeling, IoT and blockchain technologies in system design of a smart building. In: Procedia Computer Science.
[105] Kalkan E, Okur FY, Altunışık AC (2018) Applications and usability of parametric modeling. In: Journal of Construction Engineering, Management & Innovation, 1(3):139-146.
[106] https://scholar.google.com/ Accessed 25 Oct 2023.
[107] https://www.sciencedirect.com/ Accessed 25 Oct 2023.
[108] https://www.webofscience.com/wos Accessed 26 Oct 2023.
[109] https://link.springer.com/ Accessed 26 Oct 2023.
[110] https://dl.acm.org/ Accessed 26 Oct 2023.
[111] https://onlinelibrary.wiley.com/ Accessed 26 Oct 2023.
[112] https://ieeexplore.ieee.org/Xplore/home.jsp Accessed 26 Oct 2023.
[113] https://www.jstor.org/ Accessed 26 Oct 2023.

Appendix A

Table A1. RQs Addressed in Selection Studies

Study No	Author	RQ1	RQ1.1	RQ2	RQ3	RQ3.1	RQ4
[1]	[Abd, 2023]	+	+	-	+	+	-
[2]	[Afsari et al., 2019]	+	+	+	+	+	+
[3]	[Argiolas et al., 2022]	+	+	+	+	+	-
[4]	[Banerjee and Nayaka, 2021]	+	+	-	+	+	-
[5]	[Barazi, 2018]	-	-	-	+	+	+
[6]	[Barrile and Fotia, 2022]	+	+	+	-	-	-
[7]	[Bosurgi et al., 2022]	+	+	+	-	-	+
[8]	[Bueno and Fabricio, 2017]	+	+	+	+	+	-
[9]	[Chang et al., 2018]	+	+	+	+	+	-
[10]	[Chen et al., 2016]	+	+	+	-	+	-
[11]	[Chien et al., 2016]	+	+	+	-	+	+
[12]	[Chung, 2018]	+	+	+	-	+	-
[13]	[Colace et al., 2023]	-	+	+	+	+	+
[14]	[Costa et al., 2015]	-	+	-	+	+	+
[15]	[Dasgupta et al., 2019]	+	+	-	+	+	+
[16]	[Desogus et al., 2021]	+	+	+	+	+	+
[17]	[Dolas et al., 2013]	+	+	+	-	-	-
[18]	[Doukari et al., 2022]	+	+	+	+	-	+
[19]	[Fadakari, 2014]	+	+	-	-	-	-
[20]	[Fang et al., 2021]	+	-	+	-	-	+
[21]	[Fang et al., 2022]	-	-	+	+	-	+
[22]	[Fratu and Cirstolovean, 2017]	+	+	-	+	+	+
[23]	[Garagnani, 2012]	+	+	-	+	-	-
[24]	[Garagnani, 2013]	+	+	+	-	+	+
[25]	[Garagnani, 2013]	+	-	+	+	+	+
[26]	[Garagnani et al., 2012]	+	+	+	-	-	+
[27]	[Getuli et al., 2022]	+	+	+	+	+	+
[28]	[Gheisari et al., 2014]	+	-	+	-	+	-
[29]	[Ghosh et al., 2021]	+	+	-	-	-	-
[30]	[Goldman and Zarzycki, 2015]	+	+	+	+	+	-
[32]	[Gračanin et al., 2018]	+	+	-	+	+	-
[33]	[Grau-Bové et al., 2021]	+	+	+	+	+	+
[34]	[Halfawy and Froese, 2005]	+	+	-	-	-	-
[35]	[Handosa and Graˇcanin, 2017]	+	+	-	-	-	-
[36]	[Heidari et al., 2014]	+	+	-	+	-	+
[37]	[Hjelseth, 2016]	+	+	+	-	+	-
[38]	[Honcharenko et al., 2021]	+	+	-	-	+	-

Table A1. Cont'd

[39]	[Ibrahim and Krawczyk, 2003]	+	+	+	-	-	-
[40]	[Isikdag, 2015]	+	+	-	-	+	-
[41]	[Kang et al., 2022]	+	+	-	+	+	+
[42]	[Kim et al., 2021]	+	+	+	+	-	+
[43]	[Kazado et al., 2019]	+	+	+	+	+	+
[44]	[Kirchner and Huhnt, 2021]	+	-	+	+	+	+
[46]	[Kortuem et al., 2007]	+	+	-	-	-	+
[47]	[Kuzina, 2019]	+	-	-	-	-	-
[48]	[Laali et al., 2022]	+	+	+	-	+	+
[49]	[Latifah et al., 2020]	+	+	+	-	-	-
[50]	[Li et al., 2018a]	+	+	+	-	+	-
[51]	[Li et al., 2017]	+	+	+	-	+	-
[52]	[Li et al., 2020]	+	+	-	-	-	-
[53]	[Li et al., 2018b]	+	+	+	+	+	-
[54]	[Li et al., 2019]	+	+	-	-	-	-
[55]	[Liu et al., 2019]	+	-	-	-	-	-
[56]	[Lokshina and Thomas, 2019]	+	+	-	+	+	-
[57]	[Lopez et al., 2012]	+	+	-	+	+	-
[58]	[Louis and Rashid, 2018]	+	+	-	+	+	+
[59]	[Lu et al., 2021]	+	+	-	+	+	+
[60]	[Mannino et al., 2021]	+	+	-	-	-	-
[61]	[Mattern, 2003]	+	+	-	+	+	-
[62]	[Moskaliuk, 2018]	+	+	-	+	+	-
[64]	[Niu, 2016]	+	+	+	+	+	-
[65]	[Niu et al., 2019a]	+	+	+	+	+	-
[66]	[Niu et al., 2017]	+	+	+	+	+	-
[67]	[Nojedehi et al., 2022]	-	-	-	+	+	+
[68]	[Niu et al., 2019b]	+	+	-	+	+	-
[69]	[Panteli et al., 2020]	+	+	+	-	+	-
[70]	[Parsa, 2021]	+	+	+	-	-	-
[71]	[Patlakas et al., 2018]	+	+	+	+	+	+
[72]	[Pan and Zhang, 2021]	+	+	-	+	+	+
[73]	[Pocobelli et al., 2022]	+	+	+	-	+	+
[74]	[Pourzolfaghar and Helfert, 2017]	+	+	+	+	+	-
[75]	[Riccardo Giovanardi, 2021]	+	+	+	-	+	-
[76]	[Ruiz-Zafra et al., 2022]	+	+	+	+	+	-
[77]	[Sawhney and Maheswari, 2013]	+	+	+	+	+	-
[78]	[Scheffer et al., 2018]	+	+	+	+	+	+
[79]	[Scianna et al., 2018]	+	+	+	-	+	-
[80]	[Sepasgozar, 2021]	-	-	-	+	+	-
[81]	[Silverio-Fernandez et al., 2019]	+	+	-	-	+	+

Table A1. Cont'd

[82]	[Singh et al., 2015]	+	+	+	-	-	-
[82]	[M Sawhney, 2017]	+	+	+	-	-	-
[84]	[Tan et al., 2022]	+	-	-	-	-	-
[87]	[Tang et al., 2019]	+	+	-	+	+	-
[88]	[Tah et al., 2017]	+	+	-	+	+	-
[89]	[Valinejadshoubi et al., 2022]	+	+	+	-	+	+
[90]	[Volk et al., 2014]	+	+	-	+	-	-
[91]	[Sun and Kim, 2022]	+	+	+	+	+	+
[92]	[Vries et al., 2012]	+	+	-	+	+	+
[93]	[Zhai et al., 2019]	+	+	+	+	+	+
[94]	[Zhang et al., 2015]	+	+	+	+	+	-
[95]	[Zhou et al., 2021]	+	+	+	-	-	-
[96]	[Zhu et al., 2021]	+	+	+	+	+	+
[97]	[Zhu et al., 2023]	+	+	+	-	+	+
[98]	[Kaçmaz, 2019]	+	+	+	-	-	-