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TOPICAL REVIEW

Internet of Things-Building Information Modeling Integration: Attacks, Challenges, and Countermeasures

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ABSTRACT Fifth-generation (5G) technology is now being established globally and is a central topic of discussion for future generations. The building sector is at risk because the internet of things (IoT) is one of the central components of building 4.0. Building products from IBM, Amazon, Intel, Google, and Apple have demonstrated the sector's future direction. For example, IoT can be used in crowdsensing applications, where many building inhabitants submit data to building systems via smart devices such as mobile phones, smartwatches, and other means. Building information modeling (BIM) and IoT data are two distinct entities, each filling a gap left by the other. Previous research has addressed many issues, including sustainability, risk, safety, and BIM-IoT integration. This study analyzed previous studies and research on BIM and IoT data integration, as well as the challenges, benefits, and opportunities that come with it. Furthermore, this study also addressed integrating information obtained/transmitted by sensors and actuators in ways distinct from the software and platform used Using IoT in buildings can improve comfort while reducing energy use.

INDEX TERMS IoT, BIM, BMS, building management system, digital construction.

I. INTRODUCTION

Over the last decade, the construction sector has seen a shift in technological progress and interaction with the field. Several technologies, including artificial intelligence (AI), cloud computing, ontologies, blockchains, data analytics, the internet of things (IoT), laser scanning, and machine learning (ML), have benefited the construction industry. Building information is now transmitted digitally rather than on paper. Nevertheless, transformations are currently gradual and hampered by obstacles [1]. Moreover, the construction industry's progress is closely tied to the adoption of new technology. Apart from that, building information modeling (BIM) has significantly benefited the construction sector. Various players in the architecture, engineering, and construction (AEC) sector view BIM as a significant source of information sharing [2]. For instance, a BIM-based analysis of a building's degeneration over time can help develop an appropriate maintenance strategy [3]. Furthermore, BIM helps to understand the duties of many experts involved in a project, enabling them to contribute to its success and efficiency. BIM also improves collaboration between project experts [4], [5]. Due to a shortage of funds, the construction sector frequently struggles to complete building projects [6]. BIM can help mitigate these issues by identifying cost savings opportunities during the design stage of construction projects. Furthermore, an increasing number of architecture, engineering, construction, and operations (AECO) companies are using BIM to improve information management. The BIM models enable integrated information management throughout the building's life cycle, enhancing Facility Management (FM) [7]. BIM allows for more efficient design and

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construction work by developing a three-dimensional (3D) model that minimizes project interruptions and allows for time and cost computation. Alternatively, BIM permits data acquisition from various periods of the building's life cycle for use in operations management, maintenance activities, hazard assessment, and energy management simulations [8].

In addition, BIM optimizes materials and resources like plants and machinery to improve things further. Due to this development in building, BIM is becoming a widely accepted idea, and it can be used throughout a project's life cycle, from conception to completion, as well as the building phase [9], [10]. Among its main outcomes is BIM, which offers a digital description of each component of a constructed object. This model is constructed using information gathered collectively and updated at crucial project stages [11]. BIM offers several social, economic, and environmental advantages compared to conventional buildings [12]. When it comes to creating a smart city, information and communication technologies are integrated into urban planning to improve inhabitants' quality of life. Combining physical and digital infrastructures results in a Smart Infrastructure that provides more information to assist in field decision-making.

BIM can be used from the start to the finish of a project. Throughout the facility's life cycle, BIM evaluates the use of information technology (IT) in the design, administration, and legal compliance of the entire building community [13]. BIM is used to analyze models, identify conflicts, choose products, and conceptualize the entire project to enhance building projects' performance and quality. Additionally, BIM mainly supports the integrated project implementation concept (IPD) [13], a new approach to project delivery that integrates individuals, systems, business structures, and practices into collaborative processes to eliminate waste and enhance efficiency throughout the project's lifecycle [14]. This means that BIM has become a need for the design and administration of smart cities in the IoT and Big Data era. As a result, BIM use in AEC is growing [15].

Although BIM improves information management, it must be used in conjunction with new emerging technologies that may integrate new buildings by converting the construction sector into a complex environment [16]. Moreover, there is still a lack of comprehensive knowledge regarding the capabilities of current technologies, including IoT, and how they can be fully exploited beyond future BIM.

IoT is defined as ''an ecosystem of intelligent devices equipped with sensors, networking, and processing technologies that integrate and collaborate to deliver intelligent services to users.'' This ecosystem's use in health, environment, city, trade, and industry is also illustrated. IoT has enabled the unparalleled interconnection of people and objects [15], enabling a new strategy to enhance the quality of life [17]. Linked devices may also be designed to make self-sustaining judgments and educate people properly to make the best selections [17].

IoT enables different devices/objects around people to communicate by injecting powerful codes into the devices [18], [19]. The communication patterns involve various heterogeneous devices equipped with sensors like RFID (Radio Frequency Identification) tags, mobile phones, and actuators [20], [21]. The heterogeneity of devices, platforms, wireless technologies, communication protocols, and applications is one of the IoT's major characteristics and building blocks.

The emergence of IoT technology has created a world of interconnected objects, people, and services [22]. The main goal of the technology is to provide a readily available networked infrastructure using interoperable communication protocols on any network [23]. As smart technology evolves, more devices and objects can be a part of IoT through various smart sensors (e.g. wireless communication devices). Various research groups, system developers, and industries have shown interest in IoT, leading to many service applications being proposed and developed [24].

In this context, much emphasis has been placed on the use and integration of IoT and BIM to collect and store data/information throughout a building's entire life cycle. As a result, the number of innovations has increased in recent years [25]. IoT and intelligent links offer enormous potential for optimizing FM activities, including inventory and document management, building safety, logistics, and material monitoring, building life cycle tracking, and energy building controls [26]. Several studies have been conducted on utilizing data from IoT devices. However, many of them, such as the studies by Mataloto *et al.* [28] and Tang *et al.* [27], do not involve BIM integration.

Additionally, ICT-driven and IoT-based systems enable a diverse range of monitoring and control activities within built-in space, making intelligent buildings (IBs) a reality [27]. IoT has begun to permeate the building market in recent years. By effectively implementing IoT, experts from industry and academia come to understand its benefits, disadvantages, and limitations [29]. The industry's future trend has been demonstrated through products for buildings from companies like IBM, Amazon, Intel, Google, and Apple [30]. For instance, crowdsensing applications, in which many building inhabitants provide data to building systems via smart devices, such as mobile phones, smartwatches, and other ways, can leverage IoT technology [31]. The integration of IoT into buildings has the potential to increase comfort (e.g. thermal, visual, acoustic, and indoor air quality) while saving energy [31].

As previously mentioned, BIM and IoT-based data sources are relatively new concepts. BIM and IoT data can be seen as two additional entities, one covering the other's deficiency. Previous studies have addressed various aspects of BIM and IoT, including sustainability, risk, and safety. For example, energy management, construction monitoring, health and safety management, and building management are all examples where BIM and IoT devices have been used in previous research [32]–[35]. However, most studies on BIM and IoT integration are theoretical and conceptual [27], [36]. The majority of existing research can only be classified as BIM and IoT device integration without a uniform framework for transferring information across the Internet. Although the integration of BIM and IoT devices is still in its infancy, there is a need to understand the present condition of BIM and IoT device integration, which includes the following questions: What are the most common application domains for BIM and IoT device integration? What are the common BIM and IoT device integration application domains? How do BIM and IoT devices get along with one another?, and What are the research gaps and promising future research avenues that need to be addressed?.

This study seeks to answer these research concerns by doing a full assessment of BIM and IoT device integration, including a summary of application areas, integration methodologies from previous studies, an evaluation of present limits, and forecasting future research paths. This study addressed integration in a variety of ways other than through the software and platform used to obtain/transmit information from sensors and actuators (and used for a particular purpose). Therefore, this paper further analyzed studies on BIM and IoT data integration, as well as the challenges, benefits, and opportunities associated with doing so at present.

The rest of this paper is organized as follows: Section 2 discusses the state-of-the-art IoT-BIM integration; BIM implementation challenges are discussed in section 3; IoT implementation challenges are provided in Section 4; Section 5 presents the IoT-BIM operational process; Section 6 provides the application of IoT in the construction industry; Section 7 provides the proposed IoT-BIM integration framework; IoT-BIM integration benefits and opportunities are provided in section 8; Section 9 presents the conclusions of the study.

II. STATE-OF-THE-ART IoT AND BIM INTEGRATION

Numerous studies have focused on the use of BIM in the construction of various IoT devices. BIM and IoT integration is a fairly new concept in the literature [37]. BIM integration with IoT's real-time data is already a strong paradigm for increasing construction and operational efficiency for various applications. This integration, however, might obstruct people's interaction with the built environment [38]. BIM models include information about a building's functional and physical features, such as geometry, and material qualities. Data from an IoT platform can improve a dataset by giving real-time data on the current state of a building [39]. The current literature on BIM and IoT integration focuses on several areas, including energy management, building monitoring, health, safety management, and building facilities management. Nevertheless, because BIM and IoT integration research are still at an early stage, it is mostly conceptual [6]. This paper demonstrates how IoT can improve building management systems and related standards.

The following is a summary of key application areas in desperate need of new IoT edge computing (i.e. the technique of gathering, storing, processing, and analyzing data close to the client, where the data is created) applications. The technological requirements for such applications, particularly the essential quality of service (QoS), and the computer infrastructures required to operate them have been identified [40]. Among the possible areas of application are construction site management, material supply management, construction site safety and security, real-time information sharing, and communication [41].

[42] proposed a cyber-physical system (CPS) that could avoid transient structure breakdown through real-time monitoring. Furthermore, the proposed solution's support included a mobile application that utilized a cloud-based database. Similarly, Mohammed *et al.* [43] proposed a solution to alleviate crane-to-stationary barrier collisions. The proposed solution included a real-time collision control system that alerts users to impending collisions and executes appropriate security measures. Li *et al.* [44] proposed security solutions for building sites that prevent collisions between construction equipment and plant-based collisions using various surveillance systems. The proposed solution was based on RFID tags and alerts and was supported by a communication protocol and user interface. Meanwhile, Zhang *et al.* [45] outlined a strategy for evaluating the work area and utilizing RFID sensors to prevent collisions. The study proposed adopting a system for preventing plant-field accidents through the use of real-time video surveillance to increase drivers' visibility.

Additionally, several software concepts have been proposed to enhance the supply management and communication of the building process [46]. Meng *et al.* [47] described that material management substantially influences the building process; therefore, a software prototype for cost-effective construction material processing with minimal human interaction was proposed. Atazadeh *et al.* [48] proposed a web-based system that combines RFID and smart devices to improve data and information exchange efficiency on building sites. Likewise, Succar & Kassem [49] examined the management and information exchange using a multi-level computer system. Khan *et al.* [50] created an IoT-based tower crane safety surveillance system to efficiently monitor the safety of the manufacturing process. Most IoT applications created to date have been optimized to run locally or on web servers and lacked methods for reducing application/system downtime or data loss. The solutions also did not fully leverage cloud computing capabilities, such as virtualization, data replication, data migration, and orchestration across various clouds.

Moreover, high-reliability demands, including service availability, reliability, safety, security, portability, maintenance, and scalability, are common in these applications [51]. On the other hand, a few studies [28], [39], [52], [53] focused on solutions for centralized processing and storage of enormous volumes of building site data in the cloud databases. However, real-time applications are more difficult and have remained unaddressed. On-site communication breakdowns frequently result in accidents and can lead to numerous serious on-site difficulties and building delays. According to

Asadzadeh *et al.* [54], numerous communications options are available on the market. Existing communications solutions between building crews and sites are prone to mistakes. Web-based technologies are also considered possibilities for improving the procedure [55].

Many of these applications rely on various communications methods and file or information sharing between different entities; Using IoT can help improve them [56]. Several of these applications have been designed to use cloud computing, but maintaining an appropriate QoS is not always easy. During the development of applications in a single data center, the geographic locations (e.g. building sites) where automation is required change frequently as the quality of the network connections changes [57]. Because of this, centralized cloud computing solutions do not always provide the required QoS for operation. BIM-IoT device integration is examined in depth by [27], [33] to discover growing areas of application and common design principles, as well as present constraints and predictions of research possibilities. The most common areas of application were found as Construction Operations and Monitoring, Health & Safety Management, Construction Logistic & Management, and Facilities Management. Five ways of integration were outlined by the authors, including descriptions, examples, and debates. Methods for integrating BIM data into a relational database employing APIs and relational databases, as well as creating new query languages using semantic web technologies and hybrid approaches are used in these integrations. As a result of these findings, major future research paths have been proposed, including SOA patterns, web services-based techniques for BIM and IoT integration, developing standards for information management and interoperability, and cloud computing.

Based on the literature review, it can be concluded that smart building applications have great potential, but no current works have focused on the edge computing notion to meet diverse QoS needs [58]. Therefore, integrating BIM data with IoT sensors establishes a deeper data environment that can improve energy and environmental performance in buildings while lowering operating costs and consumption.

III. BIM IMPLEMENTATION CHALLENGES

BIM adoption is increasing in some countries. However, management factors need to be tackled urgently, rather than the technical aspects of efficient BIM implementation. As illustrated in Figure 1, the challenges of effective BIM implementation affect organizations and policymakers who face issues related to culture, technology, processes, and policy [58]. BIM-related issues are discussed in the following sub-sections.

A. ORGANISATIONAL CULTURE

When using BIM, a project team should recognize the degree of input required throughout the project's lifecycle, as it is an evolving technology that incorporates diverse backgrounds, experiences, and stakeholders [59]. Mannino *et al.* [52] investigated the possibility of quantity surveyor experts playing a critical role in improving the value of services in a BIM environment. Meanwhile, new positions such as BIM manager and project team structure are emerging in projects that support BIM [60]. Furthermore, BIM will soon encompass additional carrier potential in smart homes and construction industries. Therefore, clarifying the roles of team members and model users is important [61].

In addition, BIM is a cross-border system, and roles may be changed inside the organization based on the backgrounds of individuals. However, project teams must establish a new communication channel among companies and redefine the working pattern based on their partner organization, which directly affects the BIM cooperation [62].

On the other hand, the capacity of recipients to absorb and adjust to new technologies through training and education to learn about new technological innovations has a significant influence on their ability to become technology senders [63]. Similarly, following information gained via learning or training, it is not possible for BIM adopted parties to distribute their BIM expertise to other industry participants or project teams. Therefore, both formal and informal training/education is essential for employees to get an operational understanding of BIM, which entails technology application and process and information management [64].

According to previous research [28], [52], [65], education investment influences new technology adoption, where respondents were interested in the type of proficiency acquisition or optimum BIM performance [66]. Additionally, respondents urged companies or vendors to identify strategies to reduce the BIM-trained apprentice learning curve [67]. Personnel capacity and training efficiency should also be studied [68] to coordinate an appropriate training approach leading to improved productivity payback [69]; inadequate training can severely affect employees performance in handling this technological innovation. In addition, active involvement in BIM learning and the growth of dedicated staff and new personnel learning mechanisms should be promoted [69]. BIM adoption requires senior management leadership, management team empowerment, and employer devotion [70].

Importantly, management leadership also needs strong internal knowledge to speed up the adoption of BIM [71]; people can be inspired in an organization that lacks the expertise to use new technologies and decrease employee resistance to change. Ignatov and Gade [71] also stated that senior management employees' actions in the industry are necessary to influence staff and encourage readiness for changes in the process linked to cultural activities within the business. According to Zhing *et al.* [72], BIM projects still face collaboration-restricting organizational problems; collaboration is just for information exchanges rather than integrated problem solving and optimization without leaders' desire to hold teams for successful communication.

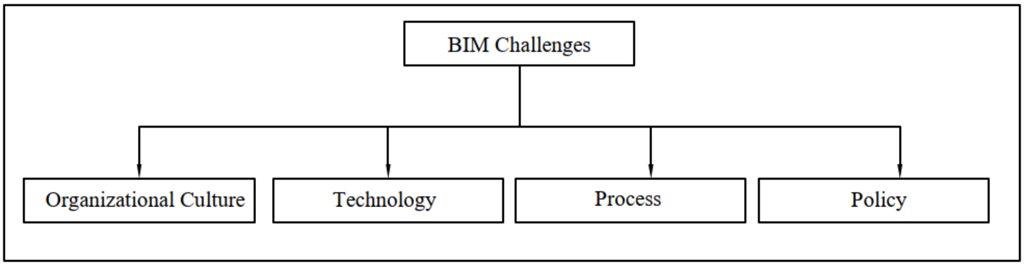

FIGURE 1. **BIM implementation challenges.**

Pacios Álvarez *et al.* [40] also mentioned the importance of visible management support and leadership to support BIM and increase employee skills in terms of training.

A sophisticated working environment requires BIM to visualize and facilitate information flows throughout the project life cycle. Nnaji and Karakhan [6] highlighted the importance of collaboration among diverse stakeholders, and the requirement for inclusion indicates the necessity for information sharing. BIM extends the range of activities available to interested parties who demand active information sharing and exchange but only a few information and resources are provided due to the lack of full adoption of the BIM technology [39]. Effective communication still depends on the human side and corporate culture. Meanwhile, BIM integration may improve confidence among the project's numerous partners [73]. Confidence in the completeness and correctness of the "Dimensional (D) models" has remained the main focus of the industrial participants, and only two-dimensional (2D) drawings are used to exchange information. Confidence is also a crucial component of successful inter-organizational cooperation connections [38].

B. TECHNOLOGY

The BIM technology has been designated a suitable medium or instrument for improving team integration to assist and coordinate the overall project information and activities [37]. Current BIM technologies vary and can give various organizational capacities. Therefore, users must examine the technology currently accessible on the market with appropriate considerations [31]. It is crucial to select the best software solutions for individual companies, and upon investment, it should be leveraged to increase the organization's potential.

In all situations, software should improve companies' capacity to communicate and exchange information confidentially with other companies [30]. Muñoz-La Rivera *et al.* [29] emphasized the necessity of BIM software selection based on a proper corporate request analysis rather than opting for marketing promotion as the project may be implemented throughout the construction phase. In addition, the selection should focus on the requirement or adequate technological capacity of project stakeholders [74] and software compatibility to share data for efficient BIM utilization [27]. Information with low compatibility cannot be successfully shared. Companies should also be attentive to safety for ensuring seamless communication. Consequently, low security constantly lowers the effectiveness of distant communication, exchange of information, and undermines stakeholder trust [74]. The insufficient expertise and abilities in BIM implementation indicate the necessity of technical assistance, especially for new adopters which could ease the BIM utilization process [27], [74].

Concerning the BIM process, several studies stated that standard papers and guidance on implementing BIM do not give clear guidance and instructions [39], [75]. As a result, stakeholders are likely to utilize BIM according to their concepts and definitions, leading to lower cooperation. A standardized BIM methodology and rules definition is required to clarify how BIM may be incorporated into current business procedures [26].

C. POLICY

BIM ownership has to be safeguarded by copyright laws and other legal channels to maintain data security and ownership. The US Architects Institute (AIA) codified and documented the regulatory regime for the digital design system, arguing that customers should have the final result [58]. Although designers no longer want to risk design flaws, they exploit this regulatory regime to justify commitments to final owners. Thus, model ownership can restrict user access and hamper security system communication [25]. In terms of procurement techniques, the BIM-based works processes demand major contractual modifications to enable stakeholders to fully participate, adopt, and assist in the growth of the technology.

While certain project delivery methods are acceptable for BIM implementations, design and build are required to maximize BIM advantages [53]. Several studies [28], [52], [72] support BIM and integrated project implementation for effective building sector cooperation. In addition, government policy can help boost implementation for early BIM adopters. Government incentives, enforcement regulations, and policies are essential for implementing BIM in projects to minimize individual resistance and change attitudes [52].

In summary, Table 1 illustrates some of the challenges and the peculiar issues associated with BIM implementation.

IV. IoT IMPLEMENTATION CHALLENGES

It is difficult to cover all IoT concerns in one article. Nonetheless, this paper summarises five key elements often addressed in connection with IoT: security, confidentiality, interoperability and standards, legal, regulation and rights, and

TABLE 1. BIM challenges and issues.

BIM Challenge Type	Peculiar Issues/Problems
Organisational Culture	BIM students' learning curve [24]; insufficient management commitment [76]; leadership challenges and need for managerial assistance [39]; difficulties in managing process change [77]; lack of teamwork, the necessity for sharing information between people, and confidence [28].
Technology	Software and hardware price [78]; selection of appropriate software [39]; lack of interoperability [79]; a need for well-developed practical techniques for the deliberate sharing and integration of useful information [54]; inadequate skills and competency, as well as a requirement for technical assistance [80].
Process	Require proper implementation standards, as is the necessity for consistency [39].
Policy	Ownership of rights and data [75]; fear of the unknown [43]; necessity for a public plan [81]

developing economies [25]. As highlighted, it is vital to promote Internet applications and services' security, confidence, dependability, resilience, and stability. Internet users require a high level of trust that the web, its applications, and its devices are safe enough to do online risk-tolerance activities they wish to conduct [24]. IoT security is distinct because it depends on consumers' trust in their environment. Individuals who lack confidence in their linked devices or information to be adequately safe from misuse or abuse are less likely to use the Internet [17]. This scenario affects worldwide e-commerce, technical innovation, freedom of speech, and almost all other aspects of internet activities. The securing of IoT goods and services should be a top concern in the field.

IoT devices' comparative costs and technological limitations challenge manufacturers to sufficiently implement security measures on these devices, producing possibly higher security and long-term maintenance vulnerabilities than their traditional computers [15]. In addition, the possibility of defects in the security design might multiply the numbers and type of the IoT devices. With so many linked IoT devices, any poorly protected online device may impair remote and global Internet safety and resilience [82]. For instance, a malware-infected unprotected refrigerator or television (TV) in the US can send thousands of spam emails to the world via the homeowners' Wi-Fi network [14]. Furthermore, in a hyper-connected society, the capacity for these devices to function in our everyday activities without the need for Internet-enabled gadgets or systems is imperative. Some non-Internet-linked devices are becoming increasingly difficult to buy as some manufacturers exclusively produce connected equipment, thus, their capacity to function adequately will be compromised [13].

People today are connected to and rely on IoT devices for essential services. There is a need to safeguard the devices while acknowledging that no device is completely safe. This increased dependence on IoT devices and Internet services with which they communicate also enhances how wrongdoers to access devices [39], [81]. Internet-linked TVs can be disconnected if they are compromised with a cyber-attack; however, an intelligent utility power meter, traffic control system, or pacemaker cannot be quickly turned off if they become victims of malice [12]. Therefore, the security of IoT devices and services is a major discussion point and should be considered a critical issue. People are increasingly dependent on these devices for essential services, and their actions may have global implications [26]. Table 2 summarises some challenges in IoT technology adoption.

TABLE 2. Challenges in IoT technology.

Components	Features	Technological Challenge	Security Challenge	Attacks Type
RFID	Unique identification tags	Tracking, DoS, and repudiation	The alteration, spoofing, and deletion	Counterfeiting and eavesdropping [83]
Sensors	Sensors and Actuators	Exhaustion and Sybil	Routing and Flooding	Tampering and Jamming [84], [85]
Wireless Sensor Network (WSN)	Receivers, radios, and receivers	Misconfiguration and access point failure	Unfairness, hijacking (equipment), loss of signal, and hacking	Malicious attacks
Near Field Communication (NFC)	Extension of RFID (NFC Tag)	Complex ecosystem, DoS	Lack of infrastructure	Eavesdropping, collision, and Maninthe-Middle (MitM) attacks [86]

The table above shows the potential security threats associated with each physical layer technology. Aspects of this layer's technology and security can be addressed by security techniques such as stenography, watermarking, encryption, intellectual property, and multimedia collection [87]. Attackers can also violate confidentiality by modifying or stealing an IoT device' identity via replay attacks. Thus, the physical layer's most important security challenges are confidentiality and privacy [85].

A. IoT IMPLEMENTATION SECURITY CHALLENGES

IoT devices tend to differ significantly from traditional computers and computer devices to address security issues. Many IoT devices, including sensors, are designed to be deployed at a huge scale beyond ordinary Internet-connected devices in terms of their magnitude [53]. As a result, there is no such thing as the potential amount of interconnected devices. Moreover, many of these gadgets can link to and communicate on their own with other devices unpredictably and dynamically. As such, existing tools, methodologies, and strategies linked to IoT security may require additional considerations [29]. Many IoT installations consist of similar or near-identical devices. With the same number of devices, a single security vulnerability can have a greater potential impact [26]. For example, a vulnerability in an Internet-enabled bulb's communications protocol could affect any product that employs or shares critical design or manufacturing features with the protocol.

Many IoT devices will be deployed for years longer than usual due to high technology gadgets with long service lives [24]. Furthermore, in conditions where reconfiguring or upgrading such devices is difficult or impossible, these gadgets may outlive their manufacturers without any means of long-standing support, leaving orphaned devices [88]. These situations show that adequate safety procedures may not suit the equipment's entire life as security concerns develop. This scenario can cause long-lasting vulnerabilities [89]. This is in contrast to the typical computer system paradigm, which is normally modified over a lifetime via operating software upgrades to cover security vulnerabilities. Therefore, IoT device long-term support and management is a major safety challenge [79].

Lastly, many IoT devices are deliberately constructed non-upgradable, or the upgrade process is lengthy/inefficient. Consider the 2015 Fiat Chrysler reminder of 1.5 million automobiles to address an assailant's wireless hacking susceptibility. These automobiles must be taken to a Fiat Chrysler dealer for a manual upgrade or upgraded via a USB (Universal Serial Bus) key by themselves [79], [90].

V. IoT-BIM OPERATIONAL PROCESS

This section explores the operational process of IoT-BIM innovation. BIM is commonly seen as a good technique for storing, organizing, and managing heavy static design and construction metadata but lacks flexibility and capacity to deal with the needs of data stocking and rapid changes to dynamic data [75]. Moreover, proper integration of IoT-BIM data can help resolve the time-consuming and computer-intensive analysis. Also, the complete life cycle of a construction project is affected - from conception to reclamation [91]. IoT's rising hyper-connection will boost the deployment of smart building ecosystems and the use of smart sensors and machine learning algorithms in automated operations [46], [92]. However, the dramatic growth in data format quantity and diversity of this approach will complicate data storage and management [93]. Growing monitoring and operating networks should comprehend and interact quickly and efficiently [93].

Building operating data is increasingly used to analyze large data and proactive BIM technology installation management [94]. Smart building operations rely on constant data collection from smart sensors. Furthermore, some smart sensors' processing power enables immediate structuring and reorganizing of sensed data [95]. Depending on the needs of the building management system (BMS), the aforementioned edge processing is employed to determine what format the data is to be shared in [96]. However, unstructured data can grow enormous, necessitating more complex searches and data mining algorithms [97]. Modern BIM uses advanced sensors that enable many buildings to become aware of their position and time, recognize their surroundings and other devices, and even forecast maintenance and repair requirements [97]. Additionally, devices and BMS must adapt their communication capabilities to the increased completeness of data interchange in these networks and systems [98].

The architecture in Figure 2 illustrates an IoT-BIM system's ability to siphon and analyze important data into any needed form.

BIM–IoT integration is still in its early phases, and considerable efforts are required to gain a deeper knowledge of the existing situation. The advantage of real-time integration of environmental and geolocation data may support functional construction and building maintenance [99]. The integration of IoT and BIM in construction management may envision the subjects' implementation in current systems [4]. BIM technology may be offered in a better platform than previously anticipated. The bottom line is that BIM's interoperable software programs and database contents enable improved usage and application of accessible data [100]. The basic rule of BIM in buildings is to give or provide data collected from any source that specifies the circumstances of these structures or original data. In any situation, valuable data might be utilized to evaluate the remodeling operation [101]. Furthermore, Table 3 summarises some recent research on integrating IoT-BIM.

VI. APPLICATION OF INTERNET OF THINGS IN CONSTRUCTION INDUSTRY (BIM)

The IoT is a smart network that connects devices and systems to the internet to automatically control, detect, and program objects [81]. Drones, construction site robots, wearable technology, monitoring sensors, three-dimensional (3D) printing, and information-sharing platforms are just a few examples of IoT uses in the present construction sector [70]. Figure 3 depicts the application areas of IoT in the BIM sector.

A. DRONE

Drones are employed primarily for two objectives in the construction sector, particularly during the building stage, namely monitoring and surveying. The drone is outfitted with a webcam to capture airborne imagery and communicate the data to project stakeholders for assessment [70]. Using the photogrammetry and 360 imaging functions of the drone, actual site progress may be documented while site scanning. Drones not only save time and money on inspections, but they also minimize safety risks because inspection personnel can evaluate structures from the ground rather than going up to them [102]–[104].

B. ROBOTS ON CONSTRUCTION SITE

Construction site robots are employed for a variety of jobs. Robotic laborers lower the quantity of on-site labor necessary [104]. They also increase productivity by reducing physical stress on workers, such as heavy lifting jobs. In Beaver County, Pennsylvania, the rebar tying robot was used in bridge building in 2017. It will be installed on an existing bridge structure, and the robot will move around the gantry, tying rebar at each junction [105]. This program contributes

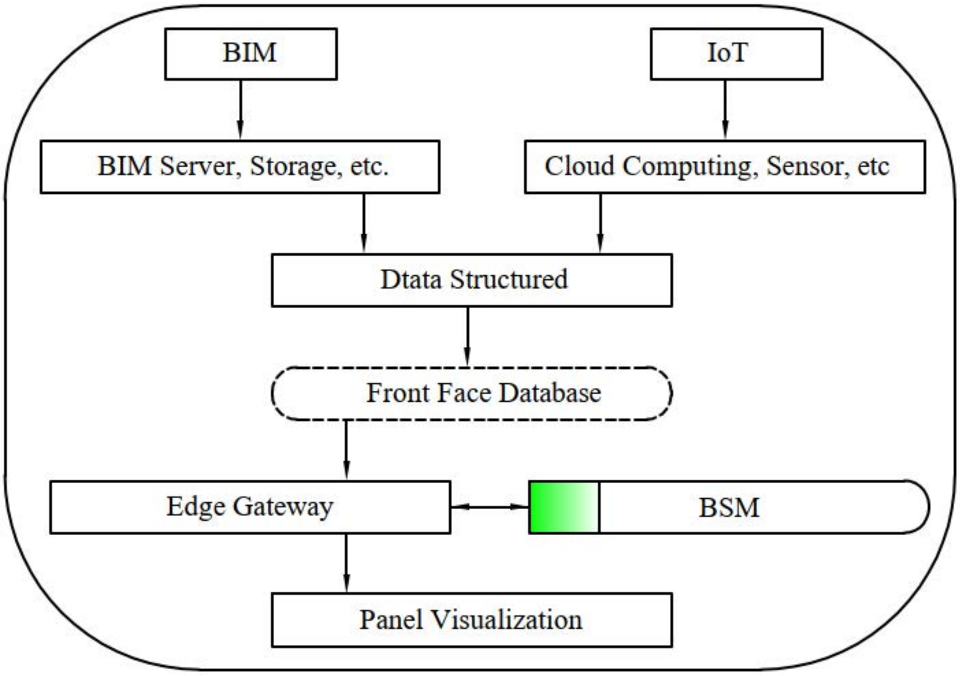

FIGURE 2. Illustration of IoT-BIM system ability.

to increasing site performance by allowing the robot to work independently once it has been set up. For major building projects, the robot is fitted with a unique arm that allows the same mechanical unit to spray plaster on both ceilings and walls [106].

C. WEARABLE TECHNOLOGY

Workers on construction sites can be equipped with wearable technology such as a smart helmet, which allows the management team to follow their whereabouts on the job site [107]. This wearable gadget is designed to alert workers on the job about any risks that may arise. It may also identify a worker's condition, such as slipping, falling, or tripping, and ensuring that the person receives immediate assistance [108]. An Australian startup has created a helmet with sensors that can monitor a worker's heart rate and body temperature while also detecting the ambient humidity and temperature [109]. The information gathered is analyzed to alert workers who may be in danger of heatstroke. The device will immediately notify the site manager of any possible workers who are in danger of heatstroke, reducing worker mishaps on the job [4].

D. MONITORING SENSORS

For a more sustainable construction, a monitoring sensor might be considered throughout the design process. Sensors can be put in construction equipment to track probable failures and plan maintenance [103]. The information gathered can be used to plan for preventative maintenance to reduce equipment failure. The Leadenhall Building in London is one of the case studies on the use of RFID sensors in construction [4]. Sensors are utilized to track specific prefabrication across the distribution network until they are installed on-site. The data obtained by the sensors help in lowering the risk of delivery delays, which have a direct impact on on-site building operations. SmartRock was created to be embedded in concrete work throughout the construction process to determine the exact strength of the concrete formed [110].

E. THREE-DIMENSIONAL (3D) PRINTING

Three-dimensional (3D) printing is projected to boost construction efficiency by decreasing the building duration. To print the construction components into specified shapes, various materials like concrete and foam are employed. In 2014, WinSun, a Chinese company, used a 3D printer to build a house. BatiPrint3D is presented in 2017, and a prototype house is built in a matter of days utilizing this innovation. 3D printing technology has been developed to build metal structures for construction projects efficiently, hence lowering the cost and waste produced [89]. The stainless steel 3D printed bridge by MX3D, a robotic metal 3D print technology developer, is an accomplishment for 3D metal printing. The concrete cycling bridge in Gemert, Netherlands, is another example of a 3D-printed bridge. The bridge was printed in parts and assembled on-site [28].

VII. PROPOSED IoT-BIM INTEGRATION FRAMEWORK

IoT is a rapidly rising global technology with numerous applications. The global installed base of IoT-linked devices has already outgrown human connections, reaching over 75.44 billion worldwide by 2025 [103]. IoT technologies include sensing, recognition, and positioning that can be communicated over the Internet via APIs (Application Programming Interfaces). The IoT devices can be employed in several applications, including safety and health, safety, and Building Administrative System (BAS) control and reporting [111]. The large amount of data generated by IoT-connected devices

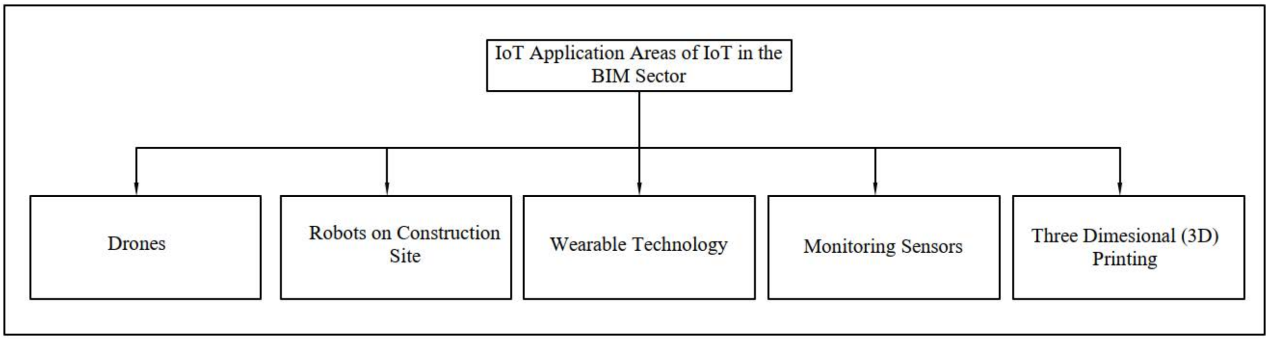

FIGURE 3. The application areas of IoT in the BIM sector.

can be analyzed in many applications. To successfully use big data in IoT-BIM systems, several functional obstacles must be overcome. Data management technologies have been a major focus for many public and commercial sector organizations over the last decade [33]. Non-smooth functions (discontinuous or non-differentiable) may have abrupt bends in their graphs, which can cause issues in power system operation. Such situations may be dealt with using several different approaches. Furthermore, an innovative approach to fire management that incorporates BIM and IoT was proposed in [70]. In this work, a possible integration concept for fire prevention and emergency management is provided between BIM tools and IoT technology. The architectural concept has been explained and the basic functional applicability of the proposed system has been performed. Finally, the benefits of this integration for building fire protection have been discussed. BIM and sensor data formatting and visualization in BMS were proposed in [71]. Data management technologies use huge volumes of dynamic data and a well-organized structure with software-specific ontology. Using BIM to provide spatial information, material qualities, orientation, etc., may help BMS provide a more accurate and intelligible analysis. Formatting and linking BIM-BMS data may assist speed up the analysis procedure. Recently, an IoT-BIM platform with permission blockchain for off-site performance measurement in structural applications was provided by [112]. The purpose of this study is to create a ''blockchain-enabled IoT-BIM platform for modular construction off-site production management''. BIM systems were developed to aid capacity planning by improving information visibility, and traceability, and fostering a more collaborative work environment. Existing systems, on the whole, have two flaws: the 'single point of breakdown' challenge of IoT networks and how to ensure the provenance of BIM updates from many sources.

This study developed a conceptual framework for the IoT-BIM data processing procedure for accessing the JSON (JavaScript Object Notation) database to better manage and store building data. The proposed framework employed a prototype to show the evidence concept. This part explains the technicalities of the prototype and describes how it would be used in a simulated scenario. The prototype was designed to illustrate the advantages of simply reformatting and linking sensor and BIM data to create a standard dataset that can be quickly and easily analyzed and resolved by FM professionals, design teams, and automated technologists.

Furthermore, the prototype was constructed using an IoT-BIM connection based on JSON formats and mapping algorithms. Sensor data were provided in limited spaces as samples of intelligent sensors that measure dust collection and the mean particle size. The samples were taken during the monitoring and supervision of the health of indoor air and ventilation ducts and included the data type created, sensor ID (identification), and value types. Figure 3 shows the proposed framework.

As seen in Figure 3, conventional BIM relies on reorganizing and processing raw sensor data, particularly when combined with other information such as location-specific environmental datasets or BIM databases. This study proposed building a large open database with basic JSON string representations that can be readily stored, sorted, and queried. The value components included sensor data and information on its monitoring records. Strings, integers, Boolean values, and arrays can be values. Sensor data for samples were gathered from a single sensor that continuously monitored the air quality in a building room and recorded a week once a day. Such intelligent time-conscious sensors produce more complex but useful data, which enables historical data analysis.

VIII. IoT-BIM INTEGRATION BENEFITS AND OPPORTUNITIES

This section explores the benefits and opportunities of integrating IoT-BIM.

A. BENEFITS OF INTEGRATING IoT-BIM

Several IoT-BIM benefits that have been recognized by researchers vary according to the short-term, long-term, or improved project or business investment. These benefits include sustainable improvement of the integrated data environment [77], design management, and knowledge. Additionally, design analysis, safety improvement, productivity, and real-time equipment monitoring are made possible at various project phases [52]. According to Atazadeh *et al.* [48] and Oyekan *et al.* [53], IoT-BIM involves creating and managing objective information with a certain property, identification, and connection.

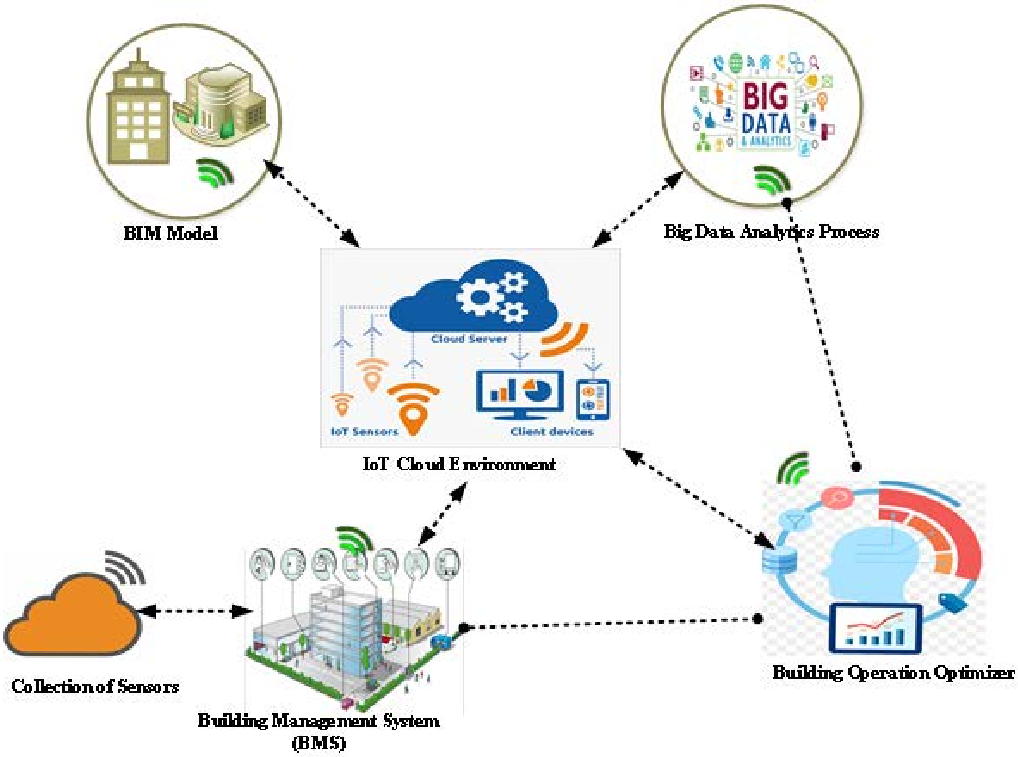

FIGURE 4. Proposed IoT-BIM integration framework.

IoT-BIM is now progressively utilized as an emerging technology to help design, develop and operate buildings in many nations. IoT-BIM was introduced in the AEC industry to solve communications and information obstacles [113]. Furthermore, IoT-BIM technology helps in improving the visualization of building actors before the actual building by virtually placing the building before physical construction [53]. Despite traditional practice, BIM technology and associated processes enable more complicated and sustainable design processes that address growing challenges while reducing building costs and subsequent usage [71]. Table 4 summarises some of the issues encountered when integrating IoT-BIM.

B. OPPORTUNITIES OF INTEGRATING IoT-BIM

1) REMOTE CONTROL OPERATION

Due to the various conditions that the building is exposed to, effective monitoring is necessary to ensure the project's smoothness. According to Panteli *et al.* [39], it is possible to provide instructions through the IoT from a great distance if machines are physically or wirelessly linked to the web. Drone-friendly equipment can be programmed to operate autonomously in monitoring zones. The drone is employed to monitor worker health and safety, as well as to conduct periodic monitoring of the construction site [77].

2) REBUILDING OF SUPPLY METHODS

The project requires an appropriate material supply for a smooth construction process [115]. However, because of the time-consuming nature of the delivery process, material cases are frequently delivered late on-site. The on-site system can automatically count the amount employing the IoT method when the supply unit is marked with an RFID tag [114]. The system communicates with the central system to place more orders if the count falls below a predetermined threshold. The RFID tags on the items make it easy to reach, understand the suitability of the product's temperature, handle properly, and notify of damage, expiration, and stock depletion [116].

3) ENGINEERING AND EQUIPMENT MAINTENANCE

Equipment maintenance is vital to minimizing the extra cost associated with heavy damages [75]. The IoT system, via the sensor method, provides information on the current state of equipment or machinery for maintenance or repair needs [117]. Khudhair *et al.* [60] stated that heavy machinery is commonly equipped with sensors that can be monitored remotely to indicate when maintenance is needed, such as temperature variations and excessive vibration. Furthermore, equipment usage exceeds the time required for equipment maintenance to be completed [72]. The IoT system can automatically log construction time through sensor scanning, ensuring that the device works promptly and warns users of its usage [74].

4) SAFE CONTROL

If the placements are not appropriately checked, material theft may occur on-site [73]. RFID tags are useful for quickly resolving any material or item theft because they provide

TABLE 3. Some recent research on integrating IoT-BIM.

Authors	Year	Techniques	Objectives
[11]	2021	Lean approaches for sustainable construction	1. The objective of this research is to discover the most current initiatives to use BIM for lean purposes during the previous decade. 2. It also intends to fill up knowledge gaps about how to use IoT in conjunction with BIM in building projects.
[70]	2020	Novel Emergency Management Devices Using BIM and IoT Technologies.	1. To propose an integrated concept for BIM tools and Internet of Things technology for prevention and mitigation and disaster response
[39]	2020	Implications of BIM in smart buildings	1. An analysis of BIM's usage in smart buildings, from design to implementation, was examined. 2. The priority was on pre-construction technologies for building projects. 3. An overview of current techniques in 4D, 5D, 6D, and 7D BIM was conducted.
[77]	2021	Combining Blockchain, the IoT, and BIM to Develop Smart Buildings	1. For security, management, and monitoring of a museum are regarded as critical considerations for the smooth running of the institution that hosts it. 2. This article analyzes the interconnectedness and interoperability of emerging technologies in the construction industry.
[42]	2020	Unification of Industry 4.0 Techniques in the Construction Industry	1. It highlights the construction industry's Industry 4.0-related technology. 2. It proposes a paradigm for integrating these technologies into a cyber-physical system.
[47]	2020	The unified uses of BIM and technological applications all across the lifecycle of a building.	1. To carefully review existing BIM applications, relevant technology integration, and trends and problems.
[10]	2020	An IoT-based system for managing safety performance in construction.	1. A novel safety model based on IoT is being developed to allow real-time management of construction site personnel and the environment. 2. The proposed approach not only detects minor accidents to lower injury rates, but it saves digital files in terms of improving access to leading and the network as a whole.

information about the current location of the material or item [24]. This sensor is installed on the main door, and the installed software enables the door to be locked and unlocked. The device can recognize visitor photos and generate an alert when sensors detect risks [68].

5) ECONOMIC MONITORING OF THE ENVIRONMENT

The integration of the IoT-BIM concept is used in environmental surveillance by a gadget called Wasp mote Plug & Sense [119]. The device comes with a remote sensor for fire,

TABLE 4. Some issues encountered when integrating IoT-BIM.

Scope	Challenges / Issues	Sensors Used	Reference
Monitoring of indoor environments	Air quality	Atmospheric pollution frequency	[71]
Environmental indoor control	Air quality	Hot weather, noise, light, gas, climate (Carbon mono oxide (CO), Carbon dioxide (CO2), Radon, Methane)	[39]
Environmental indoor control	Air quality	Thermometer, moisture, a person's wind speed	[77]
Indoor environmental surveillance	Air quality	Monoxide gas, temperatures, moisture	[12]
Indoor monitoring for the environment	Thermal convenience	Moisture content, temperatures,	[75]
Environmental indoor control	Comfort thermal	Thermographic camera temperature	[114]
Environmental indoor control	Quality of the air comfort thermal	Sunlight, CO, CO2, Temperature, moisture Sound	[35]

flood risks, and air quality monitoring. Sensors monitor the threat and transmit data to receiver centers via Wi-Fi [120].

6) HEALTH MONITORING OF THE BUILDING STRUCTURE

As a building health monitor, a linear displacement sensor is installed on structures to detect vibrations, cracks, states of building materials, and civil constructions, such as historic bridges and monuments [71].

7) INTELLIGENT COMMUNICATION AMONG BUILDINGS

Social media platforms like Facebook, Whatsapp, and Telegram are gaining popularity [38], as they can be used to communicate and exchange viewpoints, only requiring a web connection. These platforms are constantly evolving to make it easier and quicker to establish discussion groups and submit papers [45]. Meanwhile, e-tendering is another information technology (IT) instrument used in construction that leverages internet connections [4]. The e-tender idea facilitates the distribution of information to bidders. The document delivery procedure is faster because there are no further problems with distance in the system's operation. ScanMarker is a digital pen that scans any printed text and transmits it via Bluetooth to any device, including computers, tablets, and smartphones, for management purposes [39]. This device saves time by translating over 40 languages and text scans and can generate sound [121].

IX. CONCLUSION

It is crucial to understand the obstacles and opportunities associated with BIM-BMS to design an effective system. This study examined the benefits of using simple data formats, such as JSON when connecting BIM and IoT. A perspective on future developments in research is provided as the result of this paper's exhaustive literature review. The BIM approach goes beyond architectural drawings production and encompasses all the project life cycles, including design, construction, and post-construction. The earlier discussion can improve IoT-BIM adoption in the building industry. Along with these new construction technologies, the building sector is at risk, as IoT is a central component of building 4.0. Furthermore, building products from firms such as IBM, Amazon, Intel, Google, and Apple have highlighted the sector's future tendency. IoT technology, for example, can be used in crowdsensing applications, where many building inhabitants submit data to building systems via smart devices like mobile phones and smartwatches. IoT in buildings can improve comfort while saving energy. As previously mentioned, BIM and IoT data sources are nascent. BIM and IoT data can be viewed as two distinct entities that complement each other. Several previous studies addressed sustainability, risk, safety, and the integration of BIM and IoT. This study addressed the integration of information obtained/transmitted by sensors and actuators in ways not addressed by the software and platform used. As a result, this study evaluated studies and research on BIM and IoT data integration, as well as the difficulties, advantages, and present prospects. Furthermore, the difficulties of efficient BIM adoption involve organizations and politicians who must overcome cultural, technological, procedural, and political issues.

Because of the differences in communication protocols, merging BIM with real-time data presents significant interoperability issues. Adopting digital approaches and tools such as BIM during the renovation project can facilitate the execution of relevant tasks, modernize, and make the entire renovation process more efficient. Future research will include significant advances in the modeling necessary to turn building data into BIM objects with adequate precision. This includes updating the information in BIM models as well as managing with ambiguous data and objects in current building BIM models.

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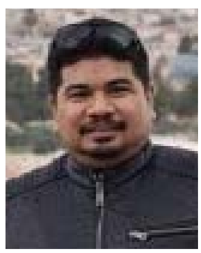

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