Review of BIM-centred IoT Deployment: State of the Art, Opportunities, and Challenges

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Abstract –

Thanks to the digital representations provided through Building Information Modeling (BIM), successful adoption of emerging digital technologies have been increasingly reported within the constriction and facility management research community. On the other hand, the number of research studies exploiting the principles of the Internet of Things (IoT) to enhance automation and control for the existing construction and facility management systems has been increasing within the last decade. By realizing the ample opportunities that can be seized through a combination of IoT and BIM, researchers have started to explore the potential benefits of BIM-centered IoT deployments. In this light, this paper aims to report the sate-of-the-art research trends for creating integration between BIM and IoT. To this end, relevant studies have been carefully reviewed to highlight the previously used sensing technologies, IoT communication protocols, BIM-centered middleware components and their ultimate application scenarios. Moreover, some of the key opportunities available through technological advancements in both IoT and BIM disciplines, along with the major open challenges threatening successful implementation of IoT-enabled BIM systems are highlighted in order to provide suggestions for future research directions.

Keywords –

Building Information Modeling (BIM), Internet of Things (IoT), Sensing technologies, BIM-centered IoT, Facility management, Construction 4.0

1 Introduction

Within the last few decades, successive waves of technological advancements have brought about the rise of the so-called 4th industrial revolution. The ultimate vision of this revolutionary movement is to blur the boundaries between physical and digital environments. The internet of things (IoT) plays a pivotal role in shaping this revolution. IoT can be viewed as networks of interconnected objects (e.g. sensors, actuators, machines, etc.) allowing real-time communications between those objects as well as communication with computer applications. Such a connectivity could significantly enhance automation and remote control of "things". Since sensors and actuators are increasingly improving in terms of power, cost, and size, more and more industries are encouraged to deploy IoT solutions [1]. The Architecture/Engineering/Construction and Facilities Management (AEC/FM) industry has been no exception to this emerging trend. Yet, according to a recent industry report published by World Economic Forum [2], this sector has been markedly slow to find its way into the mainstream of the 4th industrial revolution. This is, for the most part, due to legacy IT systems and highly fragmented nature of the construction industry.

Recently, the emergence of Building Information Modeling (BIM) has boosted hopes for expediting shifts towards a digital era for the construction industry. We have been witnessing a proliferation of research efforts for BIM during the last two decades. On the other hand, a brief look at the latest research trends reveals that there exists a growing interest among researchers to explore the potential values of the integration between IoT-driven solutions and BIM. As two emergent and fast developing technological breakthroughs, IoT and BIM offer countless opportunities for enhancing the current status of the AEC/FM industry. Evidently some of their key benefits cannot be easily achieved by approaching them separately. In this light, the research community has started paying an increasing attention to the integration of BIM and IoT. Consequently, the number of proposed BIM-centered system architectures built upon the principles of Industry 4.0, IoT, and Cyber-Physical Systems (CPS) has been rapidly growing.

This paper reviews those previous studies that have been conducted with the particular purpose of creating fusion between IoT and BIM in AEC/FM settings. By conducting this literature review, the authors pursue three main objectives: (i) identifying commonly used IoT enabler technologies that have been successfully combined with BIM-centered middleware and their corresponding domain applications, (ii) Investigating key opportunities currently available to be exploited for increasing the benefits of IoT-enabled BIM systems, and (iii) highlighting the current and future challenges for designing effective orchestrations of BIM and IoT deployment for the construction industry.

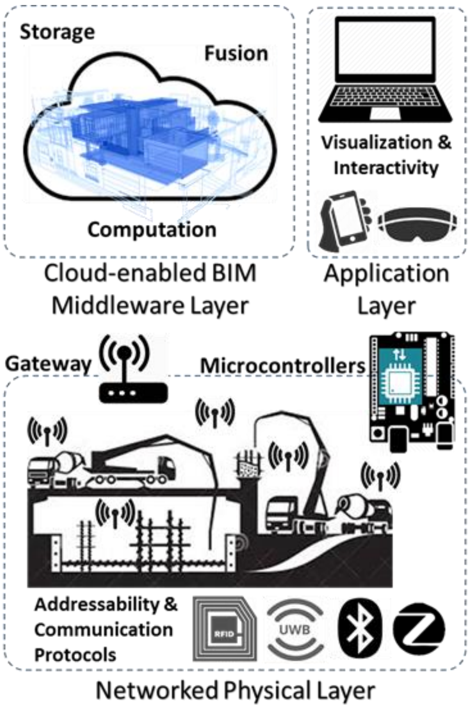

Figure 1. Conceptual framework of generic BIM-centered IoT architecture

2 Methodology

As the primary objective of this review article was set to put the current and future issues related to IoT-enabled BIM architectures into a broad perspective, the authors followed the principles of writing a narrative literature review [41]. The narrative overview presented here does not include the critique for each study reviewed. The following provides the reader with the delineation of how the present review has been conducted.

The main sources of information for this review have been selected by searching through two reputable electronic research databases namely as Science Direct, and, ASCE Library. The Google Scholar search engine was also used to ensure a reasonable breadth of potential articles. Accordingly, the three main high impact journals which together account as the primary source for the majority of the reviewed articles were: Automation in Construction, Advanced Engineering Informatics, and, Journal of Construction Engineering and Management. Moreover, in order to benefit from the knowledge in the electrical and electronics engineering domain and to bring a balanced perspective to the research issues regarding IoT development, IEEE Xplore database was also used.

The search keywords fall into two main groups each related to one of the main concepts of our primary interest. The terms within the first group which referred to the notion of BIM were: “Building Information Modeling”, “BIM”, and “BIM tools”. The keywords within the second group indicating to IoT were: “Internet of Things”, “IoT”, “Cyber-Physical Systems”, “Sensors”, “Wireless Sensor Networks”, “WSN”, “Sensing devices”, and “Remote sensing”. Different combinations of keywords from both groups were used to find articles relevant to BIM-centered IoT architectures.

Finally, the main selection criteria applied to include/exclude searching results from the review was to make sure that the research efforts reported in the searched studies have been dedicated to the creation of a seamless integration between BIM platforms and sensing devices/networks. Respectively, the selection process was done by carefully and critically reading the methodology (or architecture description) sections of the papers found within the databases. The publication time spectrum of the final candidate studies to be included in our review spans between 2011 and January of 2019.

3 State-of-the-art Research Trends

In order to create a shared sense of what is intended by “BIM-centered IoT deployment” in this paper, we present a broad definition of it on the basis of various definitions of IoT provided in [3]: remote sensing and control of physical objects within a construction site or an existing facility through seamless communication of real-time data with BIM as the unifying framework. In that sense, for the search terms used for this review, in addition to “Internet of Things”, other relevant terms such as “Cyber-Physical Systems” and “Wireless Sensor Networks” have been considered in combination with “BIM”. Hence, frameworks such as those presented in [4] and [5] which bear close correspondence to the aforementioned definition have been included in our review, though no explicit indication has been made in them to the IoT concept. Moreover, the reader should bear in mind that among existing studies with the main theme of BIM-centered IoT exploration, this review mainly deals with the most recently published ones. A conceptual framework for the generic BIM-centered IoT deployment scenario is shown in Figure 1. As it can be seen, the framework is basically divided into three main layers. The following is a summary of the state-of-the-art research trends for the architecture of our interest. Selected studies for this review are presented by taking into account the essential elements of the three layers depicted in Figure 1.

3.1 Networked Physical Layer

This layer consists of a network of physical entities which could be prefabricated building components [6], construction machinery [7], facility assets [8], [42], construction wearables [9], etc., as well as various sensor devices. Such connected entities are basically capable of communicating data with each other and to the edge of the network (to an IoT gateway for instance) in a real-time manner. In a broad sense, this layer is responsible for collecting information about physical objects and their surroundings and transferring the information to the BIM-centered middleware layer for further processing. This is done with the aid of one or more sensing technologies embedded within the network architecture. The choice for the appropriate sensing technology used in this layer depends on various factors such as the type of information that is of interest to be collected and transmitted, the rate of power consumption, implementation cost, required communication range, etc. Collected information can be about environmental conditions in construction workspaces [9], real-time location of construction workers [10], motion and orientation of building components [11], or any other useful data which could enrich the BIM model for future use. The information collected within the network is then transmitted over one or more communication medium (IoT protocols). A quick glimpse of previous proposals reveals that RFID-enabled short range communication has been the most frequent option for communicating IoT data to the BIM-centered layer. This is no surprise since RFID has been traditionally a key technology used for bringing physical objects into the digital realm through a short-range point-to-point wireless communication. Additionally, RFID tags attached to physical objects can act as distinct identifiers of those objects making them addressable within the network. Most recently, an extensive review of RFID-enabled BIM systems has been appeared in [12]. Hence, for this review we tried to include other studies that have exploited sensing technologies other than RFID and the interested reader is referred to the mentioned study for deeper insights about RFID-enabled BIM architectures. One of the emergent IoT-enablers which appears to be gaining in a rising popularity among researchers is Bluetooth Low Energy (BLE) technology, also known as Bluetooth Smart. The seminal work of Park et al. [10] is one of the pioneering examples of integrating a BIM-based system with BLE sensors used for fostering real-time location-awareness of construction workers. More recently, Teizer et al. [9], made the case for BIM-based visualizations of data about environmental conditions and workers' location in a real-time manner, with the aid of BLE beacons installed to their hard hats. Zigbee [13], is another emergent wireless communication standard famously known by its low-cost and low-power consumption rates. In [14], for the purpose of environmental monitoring of working conditions in confined spaces, researchers have developed a prototype of self-updating BIM system consuming sensor data coming from TelosB mote based sensor network which works on IEEE 802.15.4 standard (the basis for the Zigbeee specification). Another application of Zigbee-based sensor networks has been reported in [15]. In that study, the sensor network has been integrated with a multi-agent software system capable of interacting with BIM models on the basis of IFC schema to support facility management. The low data rate of indoor thermal comfort monitoring has convinced the researchers in [16] to choose Zigbee as the appropriate wireless technology for receiving and sending temperature and humidity readings to be imported into the BIM-based model of subway spaces. Despite the increasing number of studies exploiting recent sensing technologies, RFID still remains as the dominant technology used in combination with BIM systems. More discussion of opportunities available through advancements in WSNs and emergent protocols for network-based communications is given in the coming sections.

3.2 BIM-centered Middleware Layer

The main responsibility of this layer is to receive the information collected from the previous layer to be aggregated with BIM models. As depicted in Figure 1, this layer is expected to deliver three main functionalities namely as: storage, data fusion, and computation. For storage, sensor readings must be linked to a database which can be separated from or integrated with the BIM database. Since a typical IoT deployment most often encompasses multiple and heterogeneous sensing nodes, a communication medium will be needed for aggregating the multiple streams of sensor readings. To this end, an IoT gateway must be set up in order to acquire sensor datasets and prepare them to be processed and conveyed to the BIM model. As most of the reported deployments in previous studies are prototype systems, the most frequent medium used as an IoT gateway has been personal computing devices such as laptops or smartphones. In [12] for instance, with the help of an android application a smartphone was turned into an RFID-to-BIM gateway. Nevertheless, for real-world production implementations cheaper and less power-consuming computing devices such as Raspberry pi microprocessors used in [17] will be the ideal choice for the IoT gateway. Parallel with data storage, developing intelligent data fusion algorithms will be of high importance for the realization of an effective integration of IoT and BIM data. An effective data fusion scheme allows for making sense of sensor readings streaming from multiple sources, and also dealing with almost inevitable imperfections in sensor data. Although provision of such fusions will ultimately result in producing more accurate and consistent sensing data to be aggregated in BIM models, it has not been adequately investigated within the previous studies. One of the few examples in this respect can be found in [18] where a knowledge-based approach consisting of pre-defined rules has been taken to create fusion between data coming from Bluetooth beacons and motion sensors with building's geometric information. Obviously, an intelligent information fusion requires some computational power which will be provided through the third main functionality of the middleware layer: computation or data processing. It serves for data integration, automated decision-making, and action-invoking on the basis of information received from the networked physical layer and a pre-established knowledge layer. Such computational power is also essential to a proper responding to the queries raised in the application layer.

3.3 Application Layer

This layer provides BIM-based visualizations of sensing data and an end-user access to the information contained in the BIM model that has been enriched with IoT data. The most significant feature of such data access is that the needed information is retrieved in a real-time manner. This layer makes it possible for end-users to seamlessly interact with the physical layer objects through a digital interface linked to IoT actuators/microcontrollers in the networked physical layer. Actuation could be done automatically from computation module in the middleware, asked from the user for confirmation at the application layer's interface, or triggered manually by the end-user at the application layer. Various digital devices such as personal computers, smart mobile devices, and wearable computers, can provide BIM-based visualizations and the interface between the end-user and the IoT-enabled BIM system.

Since, BIM models are typically responsible for IoT data visualizations, any computing device capable of running the BIM authoring software will be a potential medium for enabling BIM visualizations that have been augmented by real-time sensing data. For example, an Ultra-Mobile Personal Computer showing the 3D BIM-model and sensor-based visualization of construction objects has been used in [7]. In [4], results of indoor localization estimations over location sensing data were visualized in a BIM authoring tool available on any computing device. By integrating fire simulations and real-time feedback information streaming from IoT sensors about the fire scene conditions, a BIM-based fire visualization and warning system for rescue planning has been realized in [19]. Another similar example of IoT visualizations in BIM software can be found in [9].

There are several application areas that have been investigated in previous studies for BIM-centered IoT architectures. Safety management has been one of the most frequent application areas reported for both construction and facility management. Accordingly, a significant portion of previous relevant studies have attempted at combining BIM-based architectures with sensor-based safety monitoring systems. In [7] for example, researchers developed a tower crane navigation system which is capable of visualizing lifted objects in the context of 3D BIM models of the under-construction building and its surroundings. Other studies have been published with the main focus on fire related safety issues [17], [19], [4]. There have been also studies investigating construction workers' safety through real-time monitoring of construction working conditions [14], [9]. Most recently, interesting application scenarios have been proposed in the context of construction 4.0. For instance, with respect to intelligent decision making for construction activities (site planning, workflow logic, etc.), application of cyber-physical systems has been proposed for enabling real-time communications among BIM-based virtual models, physical construction entities, and pre-existing knowledge bases [20], [21]. Prefabricated construction is another interesting area that researchers have contributed to by integrating BIM with sensing technologies. In [22], by developing an IoT-enabled platform established upon a BIM-based infrastructure, RFID- and GPS-based information made it possible to improve real-time traceability and visibility of the construction progress, physical building information, and cost related data in a prefabricated construction settings. Similar attempts have been reported in [23], [6], [17]. Finally, when it comes to operating facilities, energy use management and indoor comfort monitoring have been the most recurrent domain applications [16], [24], [25].

4 Opportunities

One of the most promising possibilities of the IoT solutions combined with BIM systems is that it paves the road towards creating more realistic "digital twins" for the built environment. Generally speaking, a digital twin is responsible for imitating the dynamic behavior of a given physical system. Although various technical definitions of digital twin already exist within the literature, we have adapted the one which is of our particular interest on the basis of the definition provided in [26]: a virtual representation of building components, construction processes and maintenance operations through the streams of real-time data throughout the facility lifecycle, enabling understanding, learning and reasoning about various aspects of that facility.

Through provision of digital representations of facilities' physical characteristics and functionalities, BIM models have paved the road for realization of such "digital twins". By drawing an analogy between BIM and Product Lifecycle Management in the manufacturing industry, Woodhead et al. [27] indicated that strong ties can be expected between BIM and Industry 4.0. Real-world examples of such ties have been most recently reported. In [11] for instance, researchers have been able to provide a digital twin of hoisting operations in underground construction through BIM representations standing for the virtual model of hoisting and various IoT sensing devices fulfilling real-time communications between the physical and cyber twins. Another example is a prototype of RFID-enabled BIM system presented in [8] which could be deemed as a digital twin of inspection and maintenance tasks for building assets. The evolution of BIM along with the advances in Artificial Intelligence and real-time analytics can unlock profound possibilities for the creation of digital twins with enhanced predictive capabilities for the built environment [27].

Finally, thanks to an unprecedented amount of data about building components, indoor environmental conditions, construction resources, assets, etc., that can be collected and integrated with BIM models for further processing, BIM-based immersive technologies can be more effectively deployed for AEC/FM applications. In other words, the more realistically digital twins are created for construction sites or operating facilities, the more enhanced and rich immersive experiences can be provided accordingly. Since many successful implementations of BIM-based immersive solutions such as Augmented and Virtual reality have been reported within the last two decades [28], the combination between BIM and IoT can significantly improve the effectiveness of such immersive experiences with the aid of real-time sensing data aggregated to BIM elements.

As an emerging technology, IoT can be viewed as a fast progressing filed of technology. As it was mentioned in section 3, application of RFID technology as a primary enabler of IoT has been proliferated within the existing body of knowledge. Nonetheless, owing to the continuous advancements in IoT, especially in wireless communication technologies, new opportunities are open for designing novel architectures of IoT-enabled BIM systems. Although the number of studies investigating relatively recent communication protocols such as BLE is increasing, the research community has been slow to adopt more recent advancements such as Zigbee and Lora. Hence, future research should pay more attention to this issue because such advancements most often offer new features and tackle some of the existing limitations. For the case of Zigbee for instance, the technology has already demonstrated an enormous potential for replacing traditionally used communication technologies for enabling indoor automation such as WiFi, by delivering similar functionalities at a fraction of cost and power consumption. Additionally, plenty of opportunities can be seized through developing hybrid architectures which exploit different IoT technologies within a single architecture. One prospective scenario in this regard can be explained as follows: while Zigbee will be an excellent choice for those indoor applications requiring low-rate data transitions (indoor comfort monitoring for example), it will not fulfil the requirements of the applications used in construction job-sites which generally require long range data communications. This is where adding a Lora-based module can properly address the limitation of Zigbee for long range communications. A review of Lora-based communications has been most recently reported in [29].

In summary, more experimental research should be conducted in the future to explore the potential benefits of integrating BIM systems with standalone or hybrid solutions based on emerging IoT-enabler technologies.

One of the major technological breakthroughs that has hugely contributed to the success of IoT is cloud computing. The integration of cloud computing and IoT promises new directions for both business and research [30]. Cloud computing also has made significant positive impacts on BIM. Therefore, it can be expected that the combination of cloud-enabled BIM with IoT could unlock ample opportunities for the construction industry. Such opportunities have been already realized by researchers in the construction sector for enabling more efficient procedures for storage, fusion and processing of IoT data. The cloud server used in [10] for example, has enabled a real-time communication of safety-related contextual information between a BIM-based hazard detection system and mobile devices of project participants. The generic concept of the IoT-cloud-BIM intelligent system has been thoroughly discussed in [31]. A cloud-based IoT platform has also been proposed in [23] for improving the leanness of prefabricated construction. Other examples in this regard can be found in [32], [17], and [33].

5 Challenges

IoT currently faces many challenges in general as an emerging and progressing technology. On the other hand, an effective adoption of BIM for AEC/FM has its own challenges as well. Hence, it can be expected that not only challenges facing IoT and BIM remain to be addressed individually, but also new challenges could rise when the integration of the two is considered.

Security is one of the most significant challenges for the IoT in general. IoT security can be broadly described as making sure that information about physical objects and properties collected from the networked layer is transmitted to the pre-assigned destinations. Encryption which has been the key approach to the Internet security can be also used for establishing secure communications between IoT nodes. However, currently available encryption methods are not adequately efficient to be used for addressing the IoT security [34]. In addition to security, privacy is another important issue in IoT. Generally speaking, IoT privacy deals with the ownership issues of data collected form the physical layer. In the context of IoT-enabled BIM solutions, privacy issues could constitute serious impediments to the proliferation of such systems. This is mainly due to the fact that the construction industry is fragmented in nature and different parties are typically engaged within it. From a business standpoint, aggregation of real-world data into BIM models could give rise to serious conflicts about data ownership rights between stakeholders since the construction sector has been traditionally reluctant to embrace the open data sharing culture. For instance, most of the constructor companies prefer not to share productivity-related data about their workers and machinery with other project participants (client, consultants, etc.), because it might help them for making financial claims. All in all, despite the fact such issues play a major role in shaping shifts towards digital construction and maintenance of facilities, the number of existing studies that put security and privacy issues at the center of attention for BIM and IoT integration are extremely low. Recent technological advancements in the internet security, such as Blockchain technology promises new opportunities for addressing such issues for IoT-enabled BIM systems. In this regard, Ye et al [35] have presented a theory named “Cup-of-Water” which suggests the application of Blockchain technology to securely and transparently preserve IoT data in BIM models during the whole life cycle of buildings.

In addition to challenges which are generally applicable to any IoT deployment, there exists other challenges which are specific to the BIM-centered IoT deployments. For instance, one of the main challenges of creating a seamless integration between BIM and IoT is to fill the gap between currently used schemas for BIM data representation such as IFC, and various IoT standards used for representing sensor data. To date, some attempts have been made to address this issue. Although IFC representations can greatly facilitate interoperability between various BIM platforms, mapping sensor data to IFC objects will be challenging if standardized IFC export guidelines and corresponding web parsers are not placed within the architecture in advance [36]. This issue has made the case for creating more semantically enhanced versions of IFC schema to provide the required readiness for integrating sensor readings with BIM models. In [8] for instance, the EXPRESS-based model of IFC schema has been edited manually to make allowance for interrelating BIM entities with RFID data. On the other hand, distributed and heterogeneous sources of IoT data streaming from the physical layer also urge the need for more semantically enriched IoT and BIM data representation schemas if an advanced information fusion is required. In this light, applications of formal data and knowledge representation methods have been proposed within the previous studies. In some studies such as those reported in [15], [20], and [37], researchers have attempted to exploit the formal representation capability of formal ontologies to address the sensor data integration with digital models of buildings. Most recently, results coming from real-world experimentations in [36] confirms that the open BIM paradigm holds the promise of improving the interoperability of IoT-enabled BIM deployments. Moreover, Semantic Web [38], Linked Sensor Data initiatives such as the SSN ontology [39], and Linked Building data initiatives such as ifcOWL [40] will open the door to more machine-understandable description of IoT data and more interoperable BIM-centered architectures.

6 Conclusion

This review article reported on the recent studies deploying BIM-centered IoT architectures in AEC/FM disciplines. The state-of-the-art research trends were highlighted in three main respects. First, previously used sensing technologies and network communication protocols were introduced. Next, key components of a BIM-centered middleware for an effective IoT-enabled implementation were discussed. Finally, those application areas that have reportedly benefitted from such fusion in the past, were also identified in this review.

The integration between BIM and IoT offers huge potentials for fundamentally altering the ways by which construction activities and maintenance of operating facilities are currently done. The primary promise of an IoT-enabled BIM solution is to bridge the real world construction sites and operating facilities to digitally represented models. This could remarkably contribute to joining the mainstream of the paradigm shift toward digital construction era through the possibility of creating more realistic digital twins of construction job sites and operating facilities. Such digital twins can also improve the effectiveness of utilizing other digital technologies such as virtual and augmented reality for the built environment. In the light of technological advancements in IoT networking, wireless communications and the emergence of innovative breakthroughs such as cloud computing and the Blockchain technology, more and more opportunities will be available to be exploited for enhancing the usefulness of IoT-enabled BIM systems in practice.

As this review showed, there exists a significant gap between current research efforts done and unlocking the full potential of IoT-enabled BIM systems to move towards a more digitally-enabled construction and facility management paradigm. Since the integration between IoT and BIM is still in its early stages, much research is still required to be done in order to overcome the current and future challenges. This includes but is not limited to adding more intelligent information fusion algorithms, knowledge representation and inference capabilities, and developing open standards and platforms that secure information exchange and ubiquitous compatibility across various BIM environments. Moreover, the fragmented nature of the construction industry which involves participation of different role players urges for more profound investigations over security and privacy issues for IoT-enabled BIM deployments. This will encouragingly increase the willingness of industry practitioners to take steps towards such seamlessly connected solutions.

By grasping the available opportunities and overcoming the key challenges mentioned in this review, it can be expected that more and more leaders within the construction industry will be encouraged to fully embrace digital transformation and put steps towards this inevitable entirely new paradigm.

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