# Integration of Building Information Modelling (BIM) and Sensor Technology: A Review of Current Developments and Future Outlooks

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## ABSTRACT

Building Information Modelling (BIM) is revolutionising the practicalities of current construction field, sensor technology is essential for enabling BIM to extend beyond the domain of software into the physical domain of building construction and operation; however, no prior in-depth review has focused on the integration of BIM and sensor technology. This paper provides a brief review to evaluate and clarify the state-of-art for the integration of BIM and sensor technology. A systematic review approach was adopted. The result reveals that although much research has conducted, there are gaps and scope for further work, namely: (a) More consideration of the cost of sensors needs to be taken; (b) More commercial applications should be developed; (c) Higher accuracy of positioning and tracing is needed; (d) More applications in structural design could be expanded.

## CCS CONCEPTS

• **Information Systems and Applications → Sensor information systems; Building Information Modelling**; Communication Networks →Structural sensor network

## KEYWORDS

Building Information Modelling, Sensor technology, Structural design, Construction

## 1 INTRODUCTION

Building Information Modelling (BIM) has received much attention in academia and architecture/engineering construction sector [1]. BIM is defined by the US National BIM Standard as "A digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition". In boarder terms, "BIM refers to a combination or a set of technologies and organizational solutions that are expected to increase inter-organizational and disciplinary collaboration in the construction industry and to improve the productivity and quality of the design, construction, and maintenance of buildings" [2]. From the report about construction industry informatization development of China, currently BIM involves many kinds of technology such as 3D scanning, Internet of things (IoT), GIS, 3D-printing etc. and is applicable in lots of aspects in building management. According to Isikdag [3], the first evolution of BIM was from being a shared warehouse of information to an information management strategy. Now the BIM is evolving from being an information management strategy to being a construction management method; sensor networks and IoT are technologies needed in this evolution. The information provided by the sensors integrating with the building information, becomes valuable in transforming the building information into meaningful and full state information that is more accurate and up-to-date [4].

Therefore, this paper provides a brief review to evaluate and clarify the state-of-art in the integration of BIM and sensor technology. A systematic approach was adopted in reviewing related publications. Methods of integrating the two technologies were reviewed. After elaborating the current state of research, a brief summary is given to highlight research gaps, and recommend future research.

## 2 INTRODUCTION

The review described in this paper was divided into five stages, as specified in Table 1, such as searching for literature, clarifying research directions, data evaluation, pointing out research gap and provide suggestions, and conclusion.

## 3 RESULTS

Through the review of the publications, fifty-seven (57) academic publications are identified. The result shows that the retrieved publications mainly focused on the following seven aspects: integration methods (for integrating BIM and sensor technology), sustainability, operation and maintenance, site management, structural health monitoring, positioning and tracing, and planning and design. The methods of integrating BIM and sensor technology is a fundamental research area, which forms the basis for subsequent applied research. In total, fifty (50) academic publications are related to integration method. In addition, sustainable building, site management and operation & maintenance are popular research themes; academic publications related to these aspects were sixteen, fourteen and thirteen, respectively. Further, there are seven out of 57 research related to structural health monitoring, seven out of 57 to positioning and tracing, and five out of 57 to planning and design.

**Table 1: Five-stage Analysis Framework**

| Stages | Actions | Details |
|---|---|---|
| 1 | Searching for literature | Step 1: Literature collection — Literature Databases: ASCE, Springer, Taylor & Francis, Science Direct, Emerald<br>Years: no limitation<br>Keywords: BIM Sensor<br>Selection: Publications describing sensor applications in buildings but did not discuss the integration of BIM to download<br>Step 2: Literature filtration: no relationship with sensor technology & no relationship with construction sector in article abstract<br>Step 3: Literature synthetisation |
| 2 | Clarifying research directions | Integration Methods; Sustainable Building; Site Management; Structural Health Monitoring; Operation and Maintenance; Plan and Design; Positioning and Tracing |
| 3 | Data evaluation (Findings) | Conducting a detail literature review |
| 4 | Discussion | Pointing out research gap and provide suggestions |
| 5 | Conclusion | Conclude this research |

## 3.1 Integration Methods

This part is about how BIM can be integrated with sensor technology and mainly discussed three subthemes: what kind of sensor should be chosen; how the sensors should be arranged and distributed in the building; and how to integrate BIM with data collected from sensors, which includes data processing, analysis and presentation technology. The first two subthemes are introduced in different application studies that are mainly focused on information integration technology.

Brilakis et al. [5] developed an automated algorithm for generating parametric BIM using data acquired by LiDAR (Light Detection and Ranging) or photogrammetry. The algorithm established a classification of building material prototype, shape and relationships to each other. Then the algorithm will recognize the exact element form the classification that fits special and visual descriptions. Modelers are only responsible for model checking and special elements. On this basis, Lagüela et al. [6] put forward an automated method for generating textured model. While Xiong et al. [7] proposed another integrating method, which is to learn different elements' surface features and background relationships between objects, then mark them into walls, ceilings or floors, and finally conduct detailed analysis and locate openings to the surface. Further, Isikdag [3] explained in detail about the integration methods of information provided by IoT and sensors, and integration methods of BIM and the information, in which several technical problems has been solved and a complete framework was presented.

The above subthemes provide a macro and theoretical technical framework, while some other researchers were more focused on actual implementation. Rowland [8] put forward that gamification is the future integrate direction of BIM and IoT through a research towards hospitals, this research proved that gamification can realize better interaction between people and building. Edwards et al. [9] proposed a prototype realized by using a game engine to improve the terminal clients' participation of design works, it has been proved that using game engine to realize information interaction is convenient. Moreover, Khalid et al. [10] conducted a more detailed research about evaluations of databases and data formats. In this research, two kind of database: MongoDB, which is noSQL database and MySQL, which is SQL database were compared, and two kinds of data format: XML and JSON were evaluated. What's more, Unity 3D game engine is proved to be efficient in dealing with scenes which have large number of vertices.

## 3.2 Sustainable Building

This theme is concerned with two parts: energy consumption and environment protection. Building energy consumption research focuses on energy monitoring and the establishment of a method to improve energy performance or save energy, while environmental protection research concerns about saving resources and carbon emission. Using sensors to monitor and record the use of energy/resources in buildings is the basis of the methods.

There are two methods to monitor building energy consumption. One is to embed various sensors into buildings to collect related data such as capture temperature, humidity, CO2, and power consumption data; another is to conduct external scanning to building to acquire its thermal conditions. Woo and Gleason [11] established a wireless sensor network (WSN) to collect various data related to energy usage in building, then use these data to assist building retrofit design with the participation of BIM. Different from establishing a building retrofit design assist system, Dong et al. [12] focused on an energy Fault Detection and Diagnostics (FDD) system, a building energy management system (BEMS) integrated FDD and BIM were established to save energy. Ploennigs et al. [13] developed a simple scalable model-based virtual sensor to analyze building's thermal usage using few and simple sensors. Wu et al. [14] used WSN to monitor the operation energy consumption of data center, introducing BIM to predict real time thermal performance of work environment of sever, comparing predict outcomes and historical data, the operators can quickly discover thermal hot zones and conduct intervening to improve energy efficiency. In contrast to the above research directions, Shen and Wu [15] was concerned with adjusting building kinetic façade to gain higher energy performance through acquiring sunshine data via sensors.

In environment protection subtheme, Howell et al. [16] concerned about the rational use and conservation about natural resources. They used sensor network and BIM to monitor the usage of water resources and established an intelligent management system to manage water resource smartly. Similarly, Mousa et al. [17] concerned about carbon emission from buildings. They established a quantitative relationship between carbon and energy consumption data and natural gas consumption data collected by sensors, and founded a carbon emission model via BIM, which can assist carbon emission management and related decision making.

## 3.3 Site Management

This theme includes many aspects, such as operation of site equipment, monitoring site environment, site security management and construction quality management. Among them, construction quality management will be discussed as an aspect of structural health monitoring, and literature related to positioning and tracing will also be discussed in following parts. Various types of sensor are used in site management because it involves many aspects.

Alizadehsalehia and Yitmen [18] conducted a survey of construction companies, and found that in automated construction project progress monitoring (ACCPM), in terms of popularity, Global positioning system (GPS) and wireless sensor network are important for the ACCPM. Moreover, Siddiqui [19] introduced site distribute scheme and management strategy of sensors.

The use of 3D laser scanning to generate point clouds is helpful for project progress monitoring, but several questions were raised by Han et al. [20], which are lack of details in as-planned BIM, high-level work breakdown structure (WBS) in construction schedules, and static and dynamic occlusions and incomplete data collection. Another research conducted by Gao et al. [21] concerned about BIM update according to as-built BIM generated by scanning devices, a progressively captured point cloud method was developed to evaluate the repeated information in the data cloud and make decisions about which point cloud should be merged, this update method can help project managers acquire actual BIM so that they can make reasonable decisions.

Rather than focused on generating actual as-built BIM and progress management, some other researchers concerned about site safety. Riaz et al. [22] discussed the focus point of CoSMoS (Confined Space Monitoring System) for real time safety management to reduce the harmful effects of harmful environmental hazards in the construction industry. They proposed that using sensors to collect real time site environment data, and stored the data in a SQL server, and CoSMoS is invoked as a software Revit Add In from Revit Architecture software GUI to realize data visualization, which is different form the conclusion of Khalid et al. [10] that a noSQL database is preferred. In addition, Park et al. [23] conducted site safety management in a different way, which demonstrated an automated safety monitoring approach that integrates BLE (Bluetooth Low Energy)-based location tracking, BIM, and cloud-based communication. Wu et al. [24] not only concerned about safety management, but also focused on environment protection, which suggest that using various of sensors to monitor the project, then integrate project data, 3D model, stratum data, analysis data and monitoring data into BIM to establish a BIM-based monitoring system for urban deep excavation projects. In site management, sensors can not only conduct process management and safety control, but also helpful for equipment operation. Lee et al. [25] proposed a BIM and sensor based tower crane navigation system for helping cranes with blind spots.

## 3.4 Operation and Maintenance

This direction includes many aspects, such as indoor environment monitoring and conditioning, user experience optimisation, emergency management and facility management.

Marzouk & Abdelaty [26] used wireless sensor networks to collect PM10, PM2.5, temperature and humidity data and proposed a global ranking system integrated with BIM to monitor environment quality of subway station, through which a maintenance priority indices (MPIs) has been developed to help managers with allocating funds. Additionally, Costa et al. [27] also concerned about indoor environment monitoring by integrating saving energy, improving indoor environment and users' experience, where CO2, COV's, humidity level, temperature and occupancy rate were detected via sensor. Other researchers also concerned about emergency management, but in a more detailed way. Li et al. [28] developed a BIM-centred position algorithm based on SBL (Sequence Based Localization), which is aimed to rationalise sensors' cost when obtaining higher positioning accuracy. Different from concerning about positioning, Tashakkori et al. [29] established an outdoor/indoor 3D emergency spatial model to help rescuers understanding building and surroundings, optimize the rescue route and realize indoor navigation, where the dynamic and semantic building information will be collected by indoor environment sensors. Similarly, Rüppel and Schatz [30] established a serious human rescue game and choosed agent-based simulation software FDS+Evac to conduct further consideration, using camera and RFID to test and verify the game.

## 3.5 Structural Health Monitoring

This theme is concerned about the monitoring of mechanics situation of structures and the discovery of structure defects. Structural defect can be divided into two types: structural partial defect, such as crack and over deflection of concrete elements, and structural integral defect, such as poor verticality and flatness of structural elements.

Kim et al. [31] researched about manual dangerous examinations, but using RFID to tracing workers and recording their routes, then plan an optimal route of entering into the construction site, reducing potential dangerous areas that workers may pass by and generate a report about information of dangerous area. Rather than concerning about manual structural examinations, some other researchers concerned about automated structural health examination. While Mill et al. [32] not only use laser scanning to conduct outdoor building survey, but also conduct indoor building survey using total stations, establishing geodetic network system, founding BIM by importing and merging data. This model can examine and define damage degree of façade.

Different from the above methods, a detect method was put forward by Wang et al. [33], which a system integrating BIM and LiDAR for real-time controlling the construction quality has been put forward. Additionally, Zhang and Bai [34] proposed an approach by using breakage-triggered strain sensor via RFID tags to check whether the structural deformation exceeded threshold, where the responding power to the RFID reader/antenna would change by modifying the RFID tag. This method can help engineers to recognize the strain status of structure and making decisions.

## 3.6 Positioning and Tracing

This direction is to develop a method to locate or trace facilities or people inside a building by using sensors. Positioning and tracing can be applied in many occasions, such as emergency management, site security management, user experience optimization and facility management.

Costin et al. [35] put forward that it is possible to realise resource location tracking using BIM and passive RFID, and their research in 2015 discussed the method further, in which Tekla Structures software is chosen as BIM platform and Trimble ThingMagic is selected to realize RFID technology. Through the use of API (Application Programing Interface) of software and hardware to integrate BIM and RFID, an algorithm was developed to conduct indoor positioning and tracing. This method can help with reducing 64% of wrong readings to achieve the best accuracy 1.66m. The differences between the Costin et al.'s research and the research mentioned above in Li et al. [28] is the detail of algorithm.

Rather than using RFID technologies, BLE (Bluetooth low energy) technology is used in positioning and tracing. The above research done by Park et al. [23] used BLE to locate object, through which a self-corrective knowledge based hybrid tracking system is developed. The system uses BLE bacon to acquire absolute position, and motion sensors to acquire relative position, which also integrates BIM to get the geometric information of the building to improve robustness of tracing. The result shows that this hybrid system can reduce positioning mistake rate by 42%.

## 3.7 Plan and Design

This aspect concerns about acquiring enough environment, load, use information to assist building planning and design. Sensors are effective tools for obtaining environment information. Building retrofit design to aid planning and design for energy consumption has been discussed in the sustainability section.

Mijic et al. [36] conducted a case study of Banja Luka city centre, which is about city planning via the use of BIM and GIS system, in which the LiDAR is used to collect city data and BIM is used to provide materials and shades of the buildings in the central area of the Banja Luka. Moreover, Wang [37] proposed a more intuitive method of plan and design using VR (Virtual Reality) technology in a case study of an ocean park in Iceberg, in which laser scanning and sensor are used to acquire mountain's point cloud and generate 3D terrain model, and then BIM and VR technology are used to guide construction design and conduction. As such, the method can reflect the relationships between facilities and help designers find problems quickly.

# 4 DISCUSSION

From the above results, it is clear that the integration of BIM and sensor technology has been widely researched. It is also clear that the integration is useful in many applications. In this section, by referring to the result of the review, some insights and research gap have been drawn as following:

*More Consideration of the Cost of Sensors.* By reviewing those literature, little research into the cost of sensors could be found. The costs of sensors is suspected to be a barrier to wide application of building sensor networks. More cost-effective sensors are needed. To achieve this goal, several research directions can be pursued: the first is to upgrade sensor performance, which means to develop cheaper and more powerful sensors; the second is to develop efficient and useful sensor networks by optimising distribution of sensors or data processing efficiency. Further, cost assessment research is also needed.

*More Commercial Applications.* From the review, optimizing user experience is an important aspect of commercial applications, but more commercial potentials could be realised. In future works, users' behaviour data may be collected by sensors, if possible. Data mining can uncover building occupant preferences, which is potentially useful for targeting business activities (albeit with ethical concerns).

*Higher Accuracy of Positioning and Tracing.* According to the review, the accuracy of current positioning system is over 1.5m. This accuracy is relatively adequate for indoor navigation and most site works. But the accuracy still needs to be improved to meet higher navigation and facility management requirements, which means that the higher performance sensors and more scientific algorithm need to be developed in future works.

*More Applications in Structural Design.* The integration of BIM and sensors has been used in layout plan and facility design, but applications in structural design is relatively lack of investigation. From the review, several methods of monitoring structural mechanical conditions have been developed, on the basis of that, a knowledge based containing structural mechanical monitoring data could be established to assist further restructure, expansion, and similar structures' design work. The knowledge base is also very helpful for academic research because many real "experiment data" could be referred.

## 5 CONCLUSIONS

The review has clarified and evaluated the current state-of-the-art in the integration of BIM and sensors based on the identified fifty-seven (57) publications. These publications are mainly focused on the aspects of integration methods of BIM and sensor technology, such as sustainability, site management, structural health monitoring, operation and maintenance, plan and design, and positioning and tracing. It has been discovered that integration methods have been widely researched as a fundamental aspect. Moreover, sustainability, site management, and operation and maintenance are popular research directions. Several noteworthy implications have been uncovered based on the current research gap and status of development. The cost of sensors must be considered, which could be to develop cheaper and more powerful sensors or to develop efficient and useful sensor networks. On the other hand, more commercial applications could be developed based on the potential value of human behaviour data. Higher accuracy of positioning and tracing are needed for indoor navigation and facility managements. Ultimately, more applications in structural design could be expanded based on the monitoring data of existing buildings. Future government policies associated with the integration of BIM and sensor technology should encourage the applications of BIM and sensor technology in construction. The cooperation of construction industry and information industry also needs to be further strengthened.

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