Renewable and Sustainable Energy Reviews 72 (2017) 935–949

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency

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ARTICLE INFO

Keywords:
Building Information Modelling
Building management systems
Post-construction lifecycle
Energy efficiency
n Dimensional implementations

ABSTRACT

The construction industry has been evolving to embrace sustainability. This has highlighted the necessity to inspect sustainable performances throughout the post-construction building lifecycle. Application of relevant Building Management Systems (BMS) to achieve this goal is essential. Likewise, it is vital to balance the maximization of building energy efficiency and users' desired level of comfort while employing an efficient BMS for sustainable maintenance of facility operations. The high probability of inaccurate manual building inspections plus the lack of real-time input of dynamic factors urges development of automated BMS. Therefore, Building Information Modelling (BIM) plays a key role towards automation in construction and corresponding management systems. Despite the nD capability of BIM enabling its potential practice during building lifecycle phases, designers-contractors focused primarily on the application of BIM during design-construction management stages. Moreover, integration of knowledge management systems empower handling and sharing of building maintenance information during the building lifecycle. This is essential for post-construction sustainable performance. Focusing on building energy efficiency, this article has reviewed 96 papers and suggests engagement of an Integrated Knowledge-based Building Management System using nD BIM applications (BIM-IKBMS) during the post-construction building lifecycle to advance the successful implementation of sustainable building performances.

1. Introduction

Recently, the need for inspecting sustainable performance in the post-construction building lifecycle has been emphasized by the construction industry. It is essential to meet this need by adopting certain building management systems (BMS) to achieve this goal [1]. In addition, conventional post-construction building inspection methods are not completely effective. Therefore, this research aims to propose specific utilization of BIM during building maintenance for post-construction energy efficiency.

Building Information Modelling (BIM) is considered to be the leading technology for use in Architecture, Engineering, Construction (AEC) practices. It has a critical role in enhancing the effectiveness of project delivery from the initial concept through to completion and post-construction maintenance [2,3]. BIM's introduction to the AEC industry has led to it being an undisputedly contributive technology towards advancement of AEC implementations. Furthermore, BIM's capability of nD project integrations has highlighted its potential effectiveness for being incorporated with sustainable performances [4]. Researchers have also highlighted that information gathering and modelling through BIM can reduce respective building energy consumptions [5].

The high level of global energy consumption used by the construction industry has driven the need for decreasing building energy consumption via the use of amplified sensor data and improved computational support for building controls [6]. In this regard, it is vital to balance the maximization of building energy efficiency and users' desired level of comfort while employing an efficient BMS for sustainable maintenance of facility operations overstressing the implication of post-construction building inspection.

Researchers have confirmed that application of an efficient Facility Maintenance and Management system (FMM) enables executives to detect problems and sustain the facility more effectively [7]. However, the conventional inspection method of progress tracking practice often relies solely on manual visual assessments and periodical respective reports. These logs and checklists are manually prepared to indicate the

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http://dx.doi.org/10.1016/j.rser.2016.12.061
Received 12 April 2016; Received in revised form 3 October 2016; Accepted 8 December 2016
Available online 02 February 2017
1364-0321/

project's level of adaptability with the required milestones and specifications [8]. Effectiveness and accuracy of inspection progress can be affected due to the individual's personal judgment and observational skills. Additionally, the high probability of inaccurate manual building inspections, plus the lack of real-time input of dynamic factors urges development of an automated BMS. Building Information Modelling (BIM) plays a key role towards automation in construction and corresponding management systems. However, adequate skills, competence and enthusiasm of construction role-players and contractors is important for its future success [9].

Additionally, the progression of AEC building delivery includes design, construction, contracting and maintenance. This complex process, engaging multi-layer and multi-domain information storage and exchange, necessitates integrative contributions from versatile and incorporative professional teams. Therefore, competent information sharing among players is a critical factor for success. Additionally, a proposed BIM system capable of resolving AEC interoperability complications would substantially enhance the project output and respectively the buildings' energy efficiency throughout its lifecycle [10].

Essentially, 'nD' stands for multiple dimensions for describing different hierarchies of information. Despite the nD capability of BIM, enabling its potential practice during versatile building lifecycle phases, designers-contractors have focused primarily on the application of BIM during design-construction management stages. Positive prospects for BIM exist for it to be applied throughout post-construction so that energy efficiency enhancements can be augmented. While at the same time it is possible for BIM to be used during corrective building maintenance management as a preventative measure [11].

The integration of knowledge management systems to empower handling and sharing of respective building maintenance information over the building lifecycle is essential during post-construction sustainable performances. Focusing on building energy efficiency, this article suggests engagement of an Integrated Knowledge-based Building Management System using nD BIM applications (BIM-IKBMS) during the post-construction building lifecycle to advance the implementation of sustainable building performances.

This article aims to review and investigate BIM technologies utilized for building management systems with focus on post-construction energy efficiency. Authors introduce the concept of nD BIM-Integrated Knowledge-based Building Management System (BIM-IKBMS) and elaborate on its application in building energy conservation. The article highlights the three main aspects of building energy efficiency BIM and IKBMS. The proposed system in this research is expected to offer solutions to some of the current limitations within the building energy conservation spectrum through streamlining the technical interface between different cutting-edge technologies.

Section 2 outlines the methodology that has been utilized during the review, explaining the process and stages of the research. Section 3 goes on to review building energy efficiency and evaluates the traditional methods for this field. Section 4, provides a current picture of BIM and the relevant technologies such as 3D laser scanning, Cloud BIM, etc. whilst reviewing the potential of BIM. Section 5 introduces BIM-IKBMS in detail and is followed by a conclusion section which outlines the key points for all aspects of the article.

2. Methodology

2.1. The review approach

To review the potential application of nD BIM Integrated Knowledge-based Building Management System for inspecting post construction energy efficiency, a three-step approach has been adopted.

Step 1.

The first stage inspects the conventional methods available for this objective by analyzing the reviewed papers and the background of building energy conservation. Several questions relating to building energy conservation were asked and answers were provided by the latest research findings and the values of the conventional methods. For example, this study made a comparison between pre-construction and post-construction simulations to illustrate the relationship between the occupant behavior and each driven factor of them. Finally, after conducting a deep review of the conventional method, the limitations were outlined.

Step 2.

Next, this research inspects the position of advanced technology in relation to energy conservation. Firstly, the current conditions of BIM were outlined by reviewing the latest BIM reports in different countries focusing on the BIM techniques utilized in the post construction lifecycle. From this review CAD characteristics and BIM characteristics were compared in terms of their value for adopting BIM in the construction industry. The study illustrates the applications of 3–7 dimensions of BIM respectively and introduces the nD theme. It concludes by examining the potential of BIM via the latest research findings in the BIM field and catalogues them to three parts. These parts are smart building, 3D laser scanning and surveying and cloud BIM. Finally, by summarizing the limitations discovered the study gives a future direction to overcome the existing issues.

Step 3.

The final stage discusses a proposed system. It takes cognizance of the benefits of BIM relevant technologies and the traditional method for building energy efficiency to find the technical potential of conducting building energy conservation through a BIM platform. This study reviewed the values of conventional methods and the gaps between BIM and building energy conservation fields to find the application value of merging these two technologies in building energy conservation. Particular technologies for inspection were reviewed to form the structure of the proposed system. Then based on the latest research findings, BIM-IKBMS was proposed by integrating different BIM and knowledge-based platforms. Finally, the barriers and effectiveness of the proposed system are evaluated referring to the latest relevant findings.

2.2. Data analysis

In this article, a comprehensive literature search based on the 'title/abstract/keyword' search method was carried out. The keywords used in the literature search were wide ranging and included 'Building Information Modelling (BIM)', 'knowledge-based building management system', 'building energy efficiency', 'building maintenance', 'post-construction simulation', 'pre-construction simulation', 'Post-construction occupant behavior'. The search also included 'building lifecycle assessment', 'Building management systems', 'Building automation systems', 'Radio Frequency Identification (RFID)', 'Ultra-Wide Band (UWB)', 'Global Navigation Satellite System (GNSS)', '2D imaging', 'Photogrammetry', 'three-dimensional (3D) Terrestrial Laser Scanning (TLS)',' Building data acquisition systems', 'cloud BIM', 'smart building', 'Augmented Reality (AR)', and 'knowledge-based system'. A range of highly regarded journals appeared in the search including, but not limited to: Automation in Construction, Computers in Industry, Energy and Buildings, Procedia Engineering, American Society of Civil Engineers, Advanced Engineering Informatics, Computers in Industry, Journal of Cleaner Production, Building and Environment, and Scientific World Journal. BIM technologies advanced substantially from 2009, hence publications from 2008 and earlier were excluded. After delimitation, a total of 152 publications from 2009 to Sep. 2016 were selected, the number of publications found for each year is demonstrated in Fig. 1, ranging from 1 in 2010 to 50 in 2016. A wide range of publications for each element of the review was considered, the spread of publication themes is shown in Fig. 2. Particularly, publications about BIM-IKBMS related technologies were selected with the criteria of being published after 2013, because this

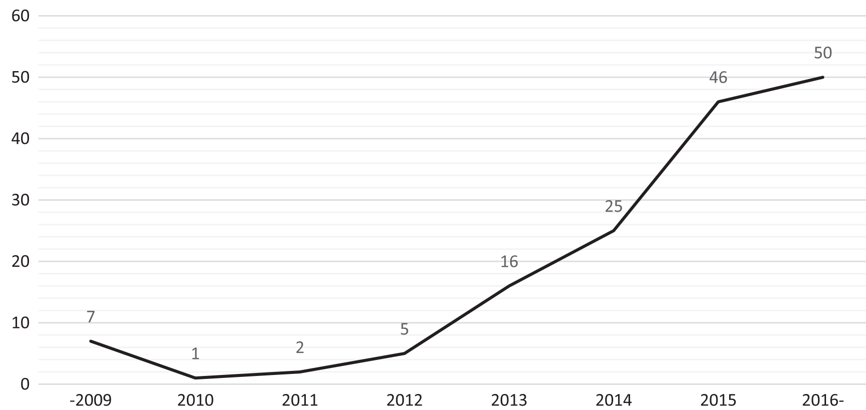

Fig. 1. Frequency of reviewed publications per year of publication.

topic was developed in the latest years.

2.3. Originality

This study has proposed nD BIM-IKBMS by combining three hot topics, including BIM, BMS and Knowledge-based Management (KM). Firstly, Building Information Modelling (BIM) is originated from Building Description System (BDS) which was proposed by Eastman [12]. This system was used for storing and manipulating building information consistently in case of design change. Subsequently, numerous BIM platforms became dependent upon the development of software technology. Secondly, Knowledge-based Management is an artificial intelligence (AI) approach for reasoning and learning from historical experience [13]. It originated from the research of Roger Schank and his students at Yale University in the early 1980s. From 2013 onwards, Knowledge-based Systems are widely used in AEC/FM industry [11]. In 2015, a knowledge-based expert system for assessing the performance level of green buildings was developed, which marks the application of a Knowledge-Based System and a Case-Based Reasoning in green building field [14]. Thirdly, BMS is a computer-based control system installed in buildings with a long history that controls and monitors the building's MEP (Mechanical, Electrical & Plumbing) equipment. After reviewing the latest publications, this study found that some researchers had made some progress on the integration of BIM and BMS [15], and BIM and KM [11]. However, the idea of combining BIM, BMS and KM was first introduced in a conference extended abstract by the authors of this study [16]. In this study, an extensive upgrade of this idea is discussed.

3. Building energy efficiency (conventional methods)

Referring to the World Energy Resources: 2013 Survey, the World Energy Council indicated that the global primary energy demand is expected to be over 1.5 fold of current demand by 2050. They also suggested that developing countries would account 80% of the growth [17]. Toward this end, energy conservation in the construction industry has become a key issue. As shown in Table 1, a system review of the current energy conservation issues was made to define the potential of energy conservation in construction industry. According to Table 1, limitations for conventional methods of energy conservation in the construction industry mainly include the lack of parametric method, integrated platform, and visualization.

Then, several questions were reviewed. How to assess building construction energy efficiency? Where the post-construction energy consumption comes from? What is the influence of the occupant behavior? What is the uncertainty in this process? How to make possible simulation throughout pre-construction and post-construction phases? How to realize the maximum energy efficiency under comfort and service constraints?

3.1. Building construction LCA and energy efficiency

Promoted by scarce resource, higher requirements for resource recycling and efficiency in the construction industry, relative communities are tending to improve the efficiency of their resource management [3]. Hence, the research and development of certain approaches that can assess building construction energy efficiency has become important. The popular and advanced approach, building lifecycle assessment (LCA) for both building materials and human activities, enables early design and decision making by providing feedback on the relevant environmental impacts. Based on this, a series of sensitivity analyses are carried out to reduce the consumption of energy. However, according to Basbagill, Flager [18] this approach is currently not flexible enough when design changes occur. Particularly, in terms of the parametric design project, with the variable parameters, LCA might lose its timeliness. Meanwhile, evaluating the environmental impacts

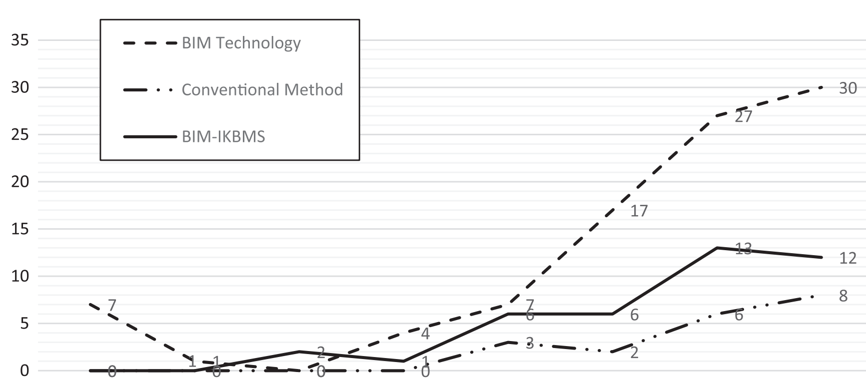

Fig. 2. Number of reviewed publications with designated topics per year.

Table 1
Post-construction energy efficiency inspection.

Limitation	Approach	Application	Aspect	Reference
Updates not timely	a) Sensitivity analysis	Largely decreases the embodied carbon footprint	Limited in design changes	[18]
	b) Dynamic & historic approach	Minimize the carbon emissions in post-construction phase	Lack of studies on the basis of the dynamic approach and the system integration	[17]
Lack of sensitivity, flexibility and non-credibility	a) Quantitative analysis and surveys	Describes a critical framework of building lifecycle assessment (LCA) for designers and decision makers	Lack of sensitivity, flexibility and non-credibility in certain aspects	[19]
Weak in integration	a) Efficiently measures the productivity change when time period changes	DEA-based Malmquist productivity index	Weak in energy management platform	[20]
	b) Building performance simulation (BPS) approach	Defines the combined effects and support the intelligent risk management	The integration of output data with non-probabilistic optimization considering both technical and economic uncertainty is needed	[21]
Lack of standards	a) Experimental methodologies	Implementation of occupant behavior models and their integration into building energy modelling programs	High data collection costs and lack of certain standards and the need to be integrated with BIM	[22]
Weak in visualization	a) EnergyPlus and MATLAB®	Simulation-based model predictive control (MPC) that achieves a smart real-time optimized regulation of the HVAC system	Need to be visualized in 3-nD	[23]

for each relevant building design parameter is significant for sustainable building design. Based on this, Hong, Koo [17] have developed a dynamic approach to track the design changes, and successfully measure the changes, but they were still limited by the lack of an integrated platform. In addition, Sami Kashkooli [19] indicated that the lack of sensitivity to the required results was a common problem for existing LCA tools. Therefore, the development of an integrated platform to provide a dynamic building LCA approach for energy efficiency could be the future direction for sustainable building design and decision making.

3.2. Post-construction energy consumption; maintenance of facility operations and energy efficiency

Post construction energy consumption accounts for a large proportion of the whole lifecycle energy consumption, hence it is important to understand the origin of post-construction energy consumption and if it is possible to control it to improve energy efficiency. Post-construction energy consumption primarily comes from the operations of the facility, which is varied in design efficiency, maintenance, and occupant behavior. Thus, a number of actions could reduce the post-construction energy consumptions including the early decision making for sustainability [18], complete maintenance information integration that enhances efficient facility operation [11] and accurate operations by occupants [22]. Meanwhile, monitoring, diagnosing and retrofitting the post-construction facility operations could also improve the energy efficiency. However, Hong, Koo [17] believed that the current monitoring, diagnosing and retrofitting technologies in the post-construction phase are limited in the lack of an integrated platform and are also need to be upgraded by researchers in a dynamic view. Meanwhile, Yan, O'Brien [22] also indicated that without integrated technologies and standardization, the data collection process would be inhibitive in terms of cost.

3.3. Post-construction occupant behavior

Occupant behavior is regarded as a key factor in building design and retrofit evaluation, however, the modelling and analysis of building energy are currently over simplified by the misunderstanding of occupant behavior [24]. Yan, O'Brien [22] studied building performance factors especially in occupant behavior, and they also completed a detailed review on the energy consumption differences in various occupants as regards to heating, lighting and other appliances, and found that energy consumption differed over 150% with different occupant-related inputs. Hong, Taylor-Lange [25] also referred to the energy consumption structure of 10 similar houses for 10 kinds of end use appliances to indicate the large variations in end use. Hence, modelling, simulation, analysis and optimization of occupant behavior are another solution to achieve energy conservation. However, the existing simulation methods have 30% uncertainties [22,25]. After the examination in occupant behavior simulation applications shown in Table 1, the future direction of this topic should be the development and optimization in simplifying and standardizing the process of data collection and model evaluation. Dealing with these problems, Hong, Taylor-Lange [25] suggested a combination with BIM that can be processed onto an integrated platform to promote the data descriptions and exchanges.

3.4. Uncertainty in real-world occupant behavior

Based on current construction methods the use of precast systems for building energy consumption is inaccurate. The results of modelling and analysis for building energy are confusing the decision makers on parameter definition. By examining the real-world occupant behavior, the aleatory uncertainties account for a higher proportion in the total uncertainties. The primary occupant behavior factors that largely

Table 2
The primary occupant behavior factors related to energy consumptions.

Primary factors	Driven factors											
	IAQ	NFO	WCS	A/D	SLH	CAT	DMV	CTO	PRS	SOR	LDU	LSP
Windows	√	√	√	√	√	√						
Blinds				√			√	√	√			
Shades			√	√						√		
Air conditioning				√	√	√					√	√
Plug loads				√								
Lighting				√								

Notes: IAQ=Indoor air quality; NFO=Noise from outside; WCS=Weather conditions; A/D=Arrival/departure & duration of absence; SLH=Sensible and latent heat; CAT=Clothing adjustment; DMV=The desire to maintain view; CTO=Connection to outdoor; PRS=Privacy reasons; SOR=Solar radiation; LDU=Long duration; LSP=Large space. Adapted from Chen, Yang [26].

influence energy consumptions and their drivers are listed in Table 2. As shown in Table 2, arrival/departure and the duration of absence most widely influence the operation conditions of the appliances, which is difficult to estimate accurately. Chen, Yang [26] categorized them into three groups, occupant, appliance operation and window/shading operation. Meanwhile, the rationality of the model simplification, the accuracy of analysis tools, and the authenticity of data collected are the main sources for systemic uncertainties. These need to be validated so that the results could be more accurate [25]. Over simplification for the occupant behavior in the building energy model is linked to the lack of understanding for the influence of occupant behavior, which is the current stage of the existing methods [22]. The accuracy of the analysis tools also needs to be validated in a wider range of scenarios [24]. Additionally the authenticity of data collected is challenged by the situational awareness of occupants [25]. They might change their behaviors when they notice that they were under survey.

3.5. Possible simulations

According to Sun, Kensek [27], certain simulations have the potential to promote energy conservation. The pre-construction simulation focuses on the internal relationship between the design parameters and their effects while the post-construction simulation focuses more on the relationship between real-world operation data and optimization actions. Table 3 shows that the pre-construction simulation methods can help decision makers by providing useful suggestions and a powerful design review while post-construction simulations highlight any inefficient operations and optimize them. Particularly, in terms of core tools, numerical simulation tools such as MATLAB are widely used throughout the construction lifecycle, however, it requires a large amount of numerical analysis. Pre-construction methods are limited in minimizing uncertainty in smart buildings, while post-construction methods are challenged by the authenticity of data collection. Thus, based on a multi-dimension model that highly integrate sustainable information and structural standards the platforms are needed to be developed for higher efficient simulations.

3.6. Maximum energy efficiency while maintaining occupant comfort and services

The balance between the maximum energy efficiency and occupant comfort and services can make a reasonable decrease in energy consumption. A careful tradeoff is required between energy conservation and operations. It is also important to realize the maximum energy efficiency under both comfort and service constraints. Kwong, Adam [28] reviewed comfort studies and the initial three steps. Step 1 is constraints setting. Human comfort conditions should be assessed. Data logger and electronic sensors are utilized in monitoring the conditions of the environment. A system assessment is then carried out to set the constraints of energy efficiency improvement. Step 2 is to consider any possible tradeoffs. It is important to utilize the comfort conditions in the building energy audit and set up the tradeoffs in both design and operations. The final stage is validation. Computer methods such as CFD are used to predict the performance and validate and optimize the design for maximum energy efficiency under constraints instead of field studies. Similarly, other products, can improve energy efficiency without reducing occupant comfort, such as a fixed air conditioner thermostat set-point. Alternatively, the adjustable appliances that occupants can alter to suit themselves would also maximize the efficiency. However, overestimating relevant factors such as the PMV index might cause comfort redundancy. Furthermore, this 3-step process should be integrated into a professional platform to avoid repeating works.

4. Building information modelling (BIM)

4.1. The current status

BIM has no universally accepted definition, it not only acts as a kind of 3D software for building design but also a multidimensional, historically evolving, complex phenomenon [9]. It can also be seen as a database, which widely ranges in attributes and relationship information of building elements. It changes the way in which buildings are designed, constructed and operated by coordinating multi-disciplinary works and integrating life cycle applications [29]. BIM is currently used in 34% of respondent projects in New Zealand and this is expected to increase to 49% for future projects [30]. NBS [31] indicated that BIM

Table 3
A comparison of pre and post construction simulations.

Phase	Purpose	Method	Energy conservation	Reference
Pre	Estimate the effects	Estimate the combine effects under uncertainties	Decision making for sustainability design	[21]
	Predict the performances	A probabilistic method on risk.	Design review	[27]
Post	Real-time control	Optimize current operations base on monitoring data.	Reduce facility operation energy consumptions	[23]
	Evaluate performance	Evaluate performance based on observation	Evaluate the process	[22]

Table 4
BIM techniques in the post-construction lifecycle.

Aspect	Achievement	Approach	Limitation	Reference
Scanning	Automate the process of as-built 3D laser scanned data	Scan-to-BIM Scan-vs-BIM	Need to be confirmed with more complex scenarios	[8]
Quality Inspection	Dimensional and surface quality assessment of precast concrete elements	3D laser scanning BIM	Limited to the single type of element, single type of scanner, the measurement noise of the sensor	[38]
As-built 3D reconstruction	Automate the process of as-built 3D reconstruction of civil infrastructure	Computer vision-based algorithms	Occlusion, accessibility, visibility, missing data, moving objects, harsh jobsite conditions, camera calibration	[39]
Structural Simulation	Convert a historic BIM into a finite element model for structural simulation	Cloud-to-BIM-to-FEM	Can be used only for modern and regular buildings with predefined object libraries	[40]
Monitoring	Monitor the environmental impacts of construction in VR	Green BIM	The lack of computer tools and the complications of the BIM models	[41]
Building energy visualization system	Visualize the process of low energy building design	BIM-GIS Web-based Visualization System	Limited in user access control and the difference in standards and data description, data format conversion	[42]
Low-carbon building (LCB) measures assessment	Select LCB measures	PROMETHEE Fuzzy LCB measures BIM	N/A	[38]
Facility Management	Improve building management and performance	7D BIM RFID	N/A	[29]
LEED certification	Integrate BIM with LEED system	BIM LEED system	This method is limited in the LEED instead of the general framework of sustainability	[43]

adoption is transforming to a more mature market. The use of BIM models in the post-construction phase is a hot research focus which is rapidly developing [32–36]. It plays a critical role in supporting Building Operation and Maintenance by providing an integrated interface for building operational performance information on all aspects [29]. Table 4 shows a wide range of BIM techniques being used in the post construction lifecycle, summarizing each aspect in turn and the approach that it utilizes. It goes on to compare each aspect's achievements and limitations. It is clear that by a combination of particular technologies such as passive RFID tags [36], 3D scanning [8], cloud computing [37], BIM can advance its adoption and achievements.

However, not all stakeholders have been able to implement BIM in the post-construction phase because of their lack of experience in using BIM [9,31]. A range of reasons for this exists and includes: BIM models in some projects are rarely updated in the construction phase by the subcontractors. So, the as-built models lose their validity for post-construction applications [9]. Secondly, a lack of knowledge/expertise will limit the potential of BIM. Subcontractors may not be motivated to upskill and understand BIM technology [30]. A lack of BIM industry standards, process and workflow in building operation and maintenance phase results in poor BIM practices and negates good coordination [30]. Furthermore, BIM software is currently developed by the vendors to integrate 3D-nD additional information into the model, such as sustainability and maintenance information [41]. It has the potential to monitor, inspect and control the performances in post-construction phase accurately [4,41] by creating a sustainable built environment based on nD visualization technology [17].

4.2. The extent of applying BIM to the construction industry

Ding, Zhou [2] conducted a literature review examining past project implementation of BIM to validate the framework of BIM applications, this suggested that BIM is improving the efficiency and effectiveness of AEC/FM industry during building lifecycles. As shown in Table 5, BIM model is distinct from 3D CAD in semantical rich information and its applications. 3D CAD methods are generally used for graphical modelling, however, BIM works create object-oriented (component-based) models enabling automatic generation of diverse drawings. Using BIM tools empowers model-based collaboration to avoid design collisions. Object-oriented models incorporate more information in multiple hierarchies, and can be used throughout the building LCA [44,45]. Meanwhile, Kivits and Furneaux [33] noted that BIM provides an automatic system for generating building information from design models and this information can largely improve the efficiency and effectiveness in the construction and post construction phase. As the implementation of building projects in the construction industry becomes more information intensive, adopting BIM can enhance visualization, communication and integration in construction operations [5]. Especially, as reducing energy consumption requires trade-offs among complex issues from different stakeholders [5], BIM could provide a platform for sharing building performance information. Basbagill, Flager [18] suggested to involve the environmental impact feedback information in BIM model for guiding the decisions of building component material and dimensions, which can reduce the energy consumption in the early stage. Lagüela, Díaz-Vilariño [46] has completed the development of information acquisition from BIM in the automatic thermographic and RGB texture system, and this can promote the energy rehabilitation for existing buildings. Lawrence, Watson [5] proposed a new BIM paradigm to reduce energy consumption by applying the principles of Energy Informatics in Facilities Management and Modelling based on BMSs. Therefore, information gathering and modelling can help reduce energy consumption within individual buildings.

4.3. 3D model to nD model

In the past decade, BIM showed its potential capacity in the AEC/FM industry by maturing from a conceptual approach to a practical system [2,4]. It is suggested that, comparing to other similar technologies, BIM still dominates the capacities for visualization [4] and cooperative [47]. According to Table 6, BIM is richer in informatization and involves more dimensions than single 3D graphical entities in CAD. Particularly, the concept of 'nD BIM' (multiple dimensional

Table 5
A Comparison of 3D CAD Vs BIM.

Aspect	3D CAD	BIM Model	Reference
Models	3D Graphical entities	3-nD integrated semantical rich information	[2]
Views	Independent 3D views that must be manually updated	Related 3D views that can be updated automatically	[2]
Methods	3D modelling	Object-oriented modelling, model-based collaboration, and network-based integration	[44]
Stages	Created in the design stage and used in the construction stage	Updated and used during building lifecycle	[45]
Collaborations	Single discipline	Multiple disciplines, all stakeholders	[45]
Functions	Producing shop drawings	Simulate the planning, design, construction, operation and maintenance of a building project	[2]

building information modelling) comprehensively describes the complex hierarchies of building information. Within a real-time cross-sectional nD BIM framework, both opportunities and challenges are provided to the project participants [4,11]. As the process increasingly becomes automatic, nD BIM oriented workflows improve the efficiency and the effectiveness of project roles. As shown in Table 6, nD BIM capacities is widely extended in different phases of the AEC industry and promote the concept of 'integrated project delivery' (IPD).

Table 6 highlights that as compared to conventional 2D drawings, 3D components can be more widely used during the building lifecycle and help to achieve multi-discipline coordination and eliminate conflicts. 3D BIM takes advantage of its related views and it is convenient for drawings to be revised given that all the drawings generated from BIM can be updated automatically [2]. Singh, Gu [47] had described a theoretical framework for the use of a BIM server that enables multi-disciplinary collaboration that can integrate more BIM-compliant applications based on 3D BIM. Oh, Lee [51] went on to improve this and proposed the integrated design system. Kerosuo [50] subsequently introduced a new idea called 'knotworking' for enhancing collaboration in BIM based projects that can reduce fragmentation of design and construction work. Other 3D BIM applications are available such as 3D scanning precast element quality inspection provided by Kim, Cheng [38], BIM based 3D games for fire safety evacuation simulations were developed by Rüppel and Schatz [52]. Thus, 3D BIM is the basis for all applications of BIM by providing a Virtual Reality environment.

By incorporating the time dimension 4D scheduling based models enable simulations for the progress of construction activities during the construction lifetime and enhance the construction schedule, quality and safety control. A number of examples of its application include: Liu, Al-Hussein [54] who provided the process of detailed construction scheduling by using 4D BIM. Tomek and Kalinichuk [55] examined the synthesis of the Agile Project Management and 4D BIM for hybrid scheduling. Earlier Kim, Anderson [53] utilized open BIM technology to extract progress information automatically and generate construction schedules. Matthews, Love [68] used 4D BIM to monitor the real time construction progress and conduct the re-engineering process while Chen and Luo [69] developed product, organization and process (POP) model based on 4D BIM to control the construction quality.

Table 6 also outlines the benefits of the adoption of a 5D estimation based model. Participants can monitor real time dynamic cash flow and benefit from making financial decisions at an early time or estimate costs by extracting quantities directly from the model. A range of 5D applications can be seen, at the early stage, Lu, Won [57] described a 5D BIM construction financial decision making framework. Cheung, Rihan [58] took out cost estimation based on 5D BIM while Choi, Kim [61] suggested an open BIM-based quantity take-off system. Likewise, Ma and Liu [60] established the approach of BIM-based intelligent acquisition of construction information for tendering of building projects (TBP) while Lee, Kim [59] applied the use of ontology-based approach in 5D BIM cost estimation. With the adoption of 5D BIM in the construction industry, the role of the 5D project cost manager is a trending position and it has been examined by Smith [56]. Additionally, the impact of BIM on labor productivity was also measured by Poirier, Staub-French [63]. Plebankiewicz, Zima [62] shared the first Polish BIM-based cost estimation case and the practicability was validated.

By attaching environmental information, 6D sustainable based BIM mainly focus on as-built operations and particular monitoring, inspection, analysis, evaluation and assessment would be conducted to track the buildings' performances. By adopting BIM, Kim, Cheng [38] developed a Fuzzy multi-criteria decision making (MCDM) model to select Low-carbon building (LCB) measures. Based on this background, integrating particular technologies can enhance the efficiency of 6D BIM. Niu, Pan [42] used BIM-GIS technology to develop a web-based building energy data visualization system to improve the design efficiency of building energy. In contrast Jalaei and Jrade [43] integrated BIM and LEED system to enhance efficient sustainable design at the conceptual design stage. Meanwhile, Wong and Zhou [41] reviewed the shortcomings of Green BIM and found current 6D BIM is far away from its full potential.

Table 6 concludes with 7D BIM. At the FM stage of the building project, 7D BIM integrates all relevant building component informa-

Table 6
nD BIM applications.

Dimension	Typical applications	Planning	Design	Construction	Operation	Maintenance	Reference
2D-Drawing	a) Design & plan b) Shop drawing generation	√	√	√			[48,49]
3D-Entities	a) Multi-disciplinary coordination b) Renderings and animation c) Digital manufacturing	√	√	√	√	√	[38,47,50–52]
4D-Scheduling	a) Construction simulations b) Quality management			√			[2,53–55]
5D-Estimation	a) Cost estimates b) Cash flow analysis	√	√	√	√		[56–63]
6D-Sustainability	a) As-built operations b) Energy consumption analysis	√	√	√	√	√	[38,41–43]
7D-Facility Management	a) Building lifecycle assessment b) Asset lifecycle management			√	√	√	[7,10,11,15,29,64–67]

tion such as product and manufacturer information, maintenance/operation manuals, etc. This can help to reduce the energy consumptions and deal with facility accidents [2]. Kivits and Furneaux [33] critically evaluated BIM in asset management and indicated that knowledge management can improve asset management. In recent years, several 7D BIM based systems were developed to promote facility management. Based on 7D BIM, Wetzel and Thabet [67] proposed a framework to support safe facility management processes while Dong, O'Neill [10] described a framework for building energy Fault Detection and Diagnostics (FDD). By merging BIM and GIS, Mignard and Nicolle [66] used ontologies in ACTIVe3D for facility management. Yenumula, Kolmer [15] developed a BIM-controlled signage system for building evacuation connected with sensors instead of computing 3D BIM data in a game engine [52]. Additionally, Motawa and Almarshad [11] developed a knowledge-based BIM system for facility maintenance and aimed to bring building information modelling to building knowledge modelling.

All of these examples support the premise that with nD BIM, practitioners can make higher level applications in AEC/FM industry during the building lifecycle and as the dimensions of BIM increase, the needs of a knowledge based system become elevated. In addition to the nD BIM developments, a number of other research areas have been reviewed in the BIM field including Smart Buildings, 3D laser scanning and surveying and cloud BIM.

4.4. BIM and smart buildings

According to Ghaffarianhoseini, Berardi [70], smart buildings are not only the buildings where facilities can be controlled remotely but also advanced in programming themselves, including monitoring the environment, generating analysis and predicting future states automatically. Volkov and Batov [71] described the distinctive feature of smart buildings stage and emphasized on its ‘intelligence’. In the previous discussion, 7D based BIM technology has shown its advantages in knowledge based facility management that is potential to structure and manage the data. However, Volkov and Batov [71] also indicated that nature of BIM is static and not suitable for smart buildings. They proposed a dynamic BIM solution that could show the construction and operation processes to fill in the gaps between BIM and "smart" buildings life-cycle. Other researchers focused on the information capture and exchange for smart building systems based on alternative systems including the COBie spreadsheet, IFC1 and gbXML format [72]. Thus, with the utilization of BIM in smart buildings, the owners would extensively benefit from the upgrade in energy efficiency and effectiveness.

4.5. 3D laser scanning and 3D building laser surveying

In the post-construction phase, 3D laser scanning is commonly used for building surveying to track the construction quality of building components. Uray, Metin [73] built 45 stations to make the 3D architectual surveying of Diyarbakir Wall’s Ulu Beden Tower possible and successfully obtained a smooth 3D model within a computer environment. Bosché, Ahmed [8] used a 3D laser scanner to inspect the dimensional and surface quality of precast concrete elements. BIM is useful as an integrated platform for the acquisition, processing and representation of point cloud data. By undertaking a comparison of as-built laser scans with as-designed BIM models, Bosché, Ahmed [8] conducted an assessessment for pipe completeness and whether built at as planned locations. Lagüela, Díaz-Vilariño [46] processed the point cloud data from 3D laser scanner to thermographic and RGB 3D Models based on as-built BIM to show the real energy conditions of the building. Due to the visualization of building real conditions, the efficiency and effectiveness of energy can be monitored, assessed and, then improved.

4.6. Cloud BIM

Although BIM is rich in its dimensions [2], even with Industrial Foundation Classes (IFC) format, construction participants onsite are always not able to obtain the information they need from a huge database. They usually need to be well-skilled and work with a high-end hardwares onsite. Otherwise, the as-built BIM might be rarely updated. Toward this end, Redmond, Hore [74] has reviewed 11 expert respondents and they proposed to develop the capacity of IFC XML and other existing technologies to promote the adoption of Cloud BIM. Accorrding to Matthews, Love [68] the use of cloud-based BIM would largely support real time construction management. By using remote web-based data servers, all construction participants can use mobile equipment or wearable device to make real-time information exchange. In addition, by avoiding complex computing onsite, Cloud BIM offers clear potetial for onsite inspection and monitoring for energy efficiency and would largely improve the effectiveness of knowledge based as-built management systems.

4.7. Futuristic BIM

BIM as a tool for use during the full building life cyle is evolving, however it does face the limitations listed in Table 4. Based on these limitations, suggested future research directions in particular technologies include:

a) The data acquisition ability through BIM based 3D scanning has been validated by current research when point-cloud data processing technologies still need to be upgraded.
b) Current smart building can only make sense in remote control for appliances while they need to be self-programming in the future.
c) Cloud BIM technologies are now being applied onsite as a mobile database and should be developed in a more detailed way in certain professional view.

On one hand, BIM techologies should be integrated in only one platform to keep the continuity of workflows. The information exchange approaches should be continuely researched such as a certain protol or standards. On the other hand, discipline-oriented research and development could improve efficiency and effectiveness of building performance. The optimization of these applications are needed to be focused on. Therefore, futuristic BIM is considered to be a ‘one-stop-shop’ BIM over the building lifecycle [41] and more complex scenarios should be confirmed to promote the BIM usability experience for certain disciplines.

5. Integrated Knowledge-based Building Management System (BIM-IKBMS)

An in-depth review of building energy conservation indicates that an integrated standard dynamic platform is the best solution to promote the effective inspection for post-construction energy efficiency. Meanwhile, as a potential technology, the dominant position of BIM in visualization, informatization, standardization, and collaboration in the post-construction is highlighted. The future direction of BIM should be more profession sensitive and integrated, ultimately, an Integrated Knowledge-based Building Management System (BIM-IKBMS) is introduced to satisfy this aim. Four elements are reviewed in this section including building construction management systems, building automation systems, building facility maintenance systems, and building data acquisition systems, as illustrated in Table 7. Based on this information the proposed system presents its potential capacity in automation, productivity, efficiency, availability and quality [8].

Table 7
ND BIM-IKBMS techniques.

N	Type	Achievement	Approach	Limitation	Reference
3D	ID	a) Develop Building Diagnosis Navigation System (BDN)	Building Medical Record (BMR)	Limited in the quality of the results and the interface of the system	[75]
		b) Develop a web-RFID-based BMS	RFID	N/A	[76]
	3D entities	a) Apply BIM in safe facility management processes	FMM	Limited in the development state of BIM.	[67]
		b) The automatic generation of textured as-built models	3D Laser scanning	Limited in level of automation of the system.	[46]
		c) Examine the benefits of a combination of BIM and 3D laser scanning technology	3D Laser scanning	Limited in the adoption of advanced technology	[77]
	Property	a) Develop AR-based Defect Inspection System	AR	Limited in level of automation	[78]
	Point cloud data	a) Introduce automatic as-is simplified BIM creation from point clouds for energy simulations	3D Laser scanning	Limited in keeping update BIM data	[79]
		b) Investigate a wide range of BIM systems in construction phase	Literature review	Limited in scope focusing predominantly on operational issues	[80]
		c) First step of classifying automated rule checking	Literature review	System environments vary	[81]
	Regulation	a) Develop a BIM-based evacuation regulation checking system	InSightBIM-Evacuation	Lack of an automated system and detailed guidelines	[82]
4D	Schedule	a) Describe a BIM-based structural framework optimization and simulation system for construction	4D simulation	Limited by current structural framework	[83]
		b) Implement a BIM-based AR system for construction	AR	Do not scale well to large models	[84]
5D	Energy	a) Develop software that can automatically couple trend data for use in ongoing commissioning and calibrating building energy models	Automatic Assisted Calibration Tool (AACT)	Limited in the compatibility of BAS and AACT	[85]
6D	Sustainability	a) Enabling sustainability and Asset Management through Knowledge Management	Literature review	Limited in IP, liability, risks, and contracts and the authenticity of users	[64]
	As-built data	a) Coordinate two different integrated project delivery platforms	Integrated Product Development	The platforms may not be formally compatible	[86]
7D	FM	a) Summarize concepts of BMS	Literature review	Limited in the problem of heterogeneity	[87]
		b) Design and development of Wired Building Automation Systems	Wired network	Limited in complex maintenance	[88]
		c) Investigates the use of DM for analyzing the large data sets in BAS	Data mining (DM)	Solid domain knowledge is still needed to apply knowledge discovered	[89]
		d) Develop a Home and Building Automation Systems	Ontology	Need to be optimized in users' view	[90]
		e) Extend the use of BAS in building energy efficiency management	2eA-FB	Limited in the utilization rate of data from BAS	[91]
		f) Describe the interface for remote operation in FM	BIM-Controlled Signage System	Limited in considering aspects	[15]
		g) Develop a 3D visualized expert system for FM	FMM	N/A	[7]
		h) Integrate Fault Detection and Diagnostics and existing Building Energy Management System in BIM	FDD + BEMS	Limited in complex process and uncertainty works	[10]
		i) Develop a knowledge-based BIM system for building maintenance	Case-Based Reasoning	Limited by the level of automation of this system	[11]
		j) Management of air-conditioning systems based on BMS	Fuzzy logic BMS	Limited by system faults	[65]
		k) Extend the application of FM in ACTIVe3D by using BIM and GIS	ACTIVe3D	Lack of the use of a database to store ontology instances	[66]
nD	Risk	a) Extend 8D BIM in accident prevention	8D Modelling Tool	Lack of proposed system to validate	[92]

5.1. BIM in pre-construction, construction and post-construction management

According to Monteiro, Mêda [86], BIM is an excellent, centralized platform for integrated works among pre-construction, during construction and for post-construction management, and a coordinated workflow could be provided on BIM platform. Several management systems in construction works are listed in Table 7. In the pre-construction phase, design review and rule checking systems were implemented on BIM platform by Solihin and Eastman [81]. Several relevant simulations were run on BIM platform for optimizing the construction process such as structural simulation [83] and construction schedule simulation [53]. During the construction process, an Augmented Reality (AR) or Virtual Reality (VR) based presentation system could improve the efficiency to monitoring, defection, inspection and management on BIM platform [78,84]. Sustainable assessment should be made throughout the construction process [93]. After construction, the BIM platform was utilized for several inspections, it is suggested that post-construction assessments should be made before operation to control the quality [38,94]. As Table 7 illustrates, pre-construction BIM focuses on design review while in the post-construction phase BIM concentrates more on evaluation. As Table 7 shows, throughout construction, BIM is centralized in simulation. Therefore, the BIM platform has a potential for facilitating improvement in the constructions' quality, efficiency and productivity.

5.2. Current building management and building automation systems

With a high proportion to total energy consumption, buildings make significant impacts on indoor human activity. According to Klein, Kwak [6], there is a growing trend for building energy conservation whereby the building control is completed by increasing sensor data and computational support. Toward this end, Xiao and Fan [89] reviewed that Building Management Systems (BMS) currently provides a smart control for actual building operation, the demand for both is increasing for the energy-intensive and information-intensive building conditions. They provide a distributed system oriented to the management and computerized control for building services [85,87]. Then, Domingues, Carreira [87] summarized the concepts and requirements of BMS, to standardize the process. Ippolito, Riva Sanseverino [1] also noted that these systems could help to improve building performance by smart use, control and interaction of appliances and domestic devices. Camacho, Carreira [90] developed a Home and Building Automation Systems and Mousavi and Vyatkin [91] extended the use of BAS in building energy efficiency management. While Zibin, Zmeureanu [85] developed software for building energy model calibration. However, current BAS or BMS lacks real-time dynamic data acquisition for occupant behaviors. From previous illustrations, the occupant behavior that can largely impact energy efficiency should also be simplified, standardized and integrated. Klein, Kwak [6] suggested to optimize the building energy and comfort with the help of both computational support and a real-world interface. Additionally Klein, Kwak [6] tried to make data mining in BAS for building performance improvement. Chen et, al. (2013) have introduced a 3D-facility-model-based system to conduct facility maintenance and management (FMM). They indicated that effective FMM systems can integrate sensor records and design documents, which can benefit early decision making and facility operation processes from their rich information. Bhatt and Verma [88] designed and developed a wired building automation system that could be connected with real-time data and dynamic management. Furthermore, an nD BIM model could largely improve the informatization of BAS or BMS and is expected to achieve smart building in the future instead of remote control.

5.3. Fuzzy logic BIM-based automated building management system

Due to the high uncertainty in the post-construction phase, especially in occupant behavior, a fuzzy logic based system is required for building operation control and management. Rather than conventional ON/OFF controller, fuzzy logic controllers can save more energy on nonlinear operations [95]. It is widely indicated that fuzzy logic method should be further emphasized on in social behavior decision making [96]. Rezeka, Attia [65] used fuzzy logic control (FLC) in BMS to manage HVAC systems based on human experience. Meanwhile, the tradeoff between maximum energy efficiency and occupant comfort is essential in energy conservation. Toward this end, Ghadi, Rasul [97] designed and developed fuzzy logic controllers for smart building that could provide indoor thermal comfort by making nonlinear control and reduced energy consumption. However, current simulation tools in the post-construction phase are not uniform in terms of standards or workflows. Kim, Cheng [38] introduced BIM into fuzzy logic systems to improve interoperability and achieve seamless data exchange. Rezeka, Attia and Saleh also suggested that the BMS can keep errors within the acceptable limits for different fuzzy logic operating modes [65]. Therefore, a fuzzy logic BIM based BMS or BAS could reduce the energy consumption by automatic accurate nonlinear control.

5.4. Augmented Reality (AR) and RFID in building data collection – Automating the project inspection

Inspection technology has been described as one of the core technologies in construction and post-construction management. Typical approaches for data collection such as Radio Frequency Identification (RFID), Ultra-Wide Band (UWB), Global Navigation Satellite System (GNSS), 2D imaging, Photogrammetry and three-dimensional (3D) Terrestrial Laser Scanning (TLS) largely improve the automation of the process [8]. Table 8 demonstrates the theory of each approach and their characteristics.

Comprehensive research by Bosché, Ahmed [8] indicated that 3D TLS is the best available technology for high accuracy and speed 3D information acquisition in AEC/FM industry, while Ko [76] emphasized RFID for its convenience and automation in data collection. Both approaches provide excellent performances in cooperation with BIM.

Meanwhile, AR technology, combining virtual and real-world objects in real time provide a good dynamic processing for the collected data. Park, Lee [78] indicated that inspection information, including virtual shapes and dimensions could be confirmed in an automatic way, and this approach could be innovative to control the process proactively and improve manual inspection practices.

5.5. Integrated knowledge-based BIM (BIM-IKBMS) system for inspecting the energy efficiency

Building maintenance (BM) is carried out throughout the facility management phase to keep facilities operating well. Efficient building maintenance could ensure a continuous comfort for occupants and also would reduce energy consumption by providing efficient control. nD BIM-IKBMS refers to a specific intelligent building management system (IBMS) in the field of AEC/FM industry that utilizes a knowledge base and Building Information Model (BIM) to promote the integration of nD building information and facilitate energy efficient building. Fig. 3 illustrate the framework of nD BIM-IKBMS modules for BM. The proposed system is composed of 5 functional parts, including the BIM module, simulation module, fault detection and diagnosis (FDD) module, BMS, and CBR module. Based on as-built BIM, this system can pre-process the raw data from BMS. Based upon this structure, the processed data can be checked with certain regulations for fault detection and with simulated results for operation optimization [10]. Subsequently the system can obtain solution cases by retrieving the faults in the knowledge base [75]. Finally, this system

Table 8
Approaches for energy inspection.

Approach	Theory	Component	Radio signal	2D	3D	Reference
RFID	A wireless sensor for electromagnetic signal detection.	Antenna	√			[98–101]
		Transceiver				
		Transponder				
UWB	Transmit radio energy at specific time intervals and occupying a large bandwidth.	Transmitter	√			[102–105]
		Receiver				
GNSS	Use satellites radio to precisely locate small receivers' location.	Small electronic receiver	√			[106–108]
		Satellite system				
2D Imaging	Imaging 2D image from sensor data.	Sensor		√		[109–111]
Photogrammetry	Making measurements from photographs.	Camera		√	√	[112–114]
		Detection component				
3D TLS	Capture surfaces by 3D point-cloud data.	3D Scanner			√	[115–118]

obtains the optimized commands that can be conducted through BMS on real-world appliances for post-construction energy efficiency.

The BIM Model: Multiple dimensional BIM models can provide a wide range of information with a clear structure. Dong, O'Neill [10] argued that the current Fault Detection and Diagnostics (FDD) system requires efficient building information exchanges. Thus, the proposed system centralized nD BIM and uses IFC protocol to promote the communication through information sharing.

Simulation Modules: The raw data collected from sensors would be preprocessed for building energy simulation. Possible simulations based on BIM can represent design information more intuitively. The faults detected by this module can be provided to the FDD Module for solution retrieval. Simultaneously, a pre-construction simulation also made a design review for BIM models.

The FDD Module: The FDD Module was established based on a principle-based model. Monitoring data could be analyzed and checked based on these principles and then the module would give out the FDD results including a problem description which would be sent to CBR Module.

The CBR Module: After the problem description was obtained, the CBR Module would retrieve the similar previous experience of building maintenance in knowledge base and capture the solve cases. According to Motawa and Almarshad [11], the knowledge-based system would provide a good collection of previous experience, history and operations for the building element so that the maintenance teams could take efficient implements for certain cases. Thus, the solved cases would be utilized in building maintenance schema making and optimization of facility operations, which could be used in BAS for automatic control. The description of the finalized case would also be retained in the knowledge base for the next retrieving.

BMS: The BMS could collect data through several approaches such as RFID, AR, 3D TLS, etc. and provided automatic controls based on the feedback in a fuzzy logic. Furthermore, the smart building could be achieved while BMS systems could program themselves.

Generally, the proposed system has integrated BIM, BAS, Knowledge-based systems and other particular technologies that aim to make tradeoffs themselves. However, computers with the proposed system of software should be prepared onsite, which may not be convenient for onsite works. Particularly, Cloud BIM technology could be suggested for onsite mobile devices enabling efficient real-time control. Motawa and Almarshad [11] have developed a Web-based Module in their system for this purpose. Thus, the interaction of users should be reduced gradually in the future by improving the automation of systems.

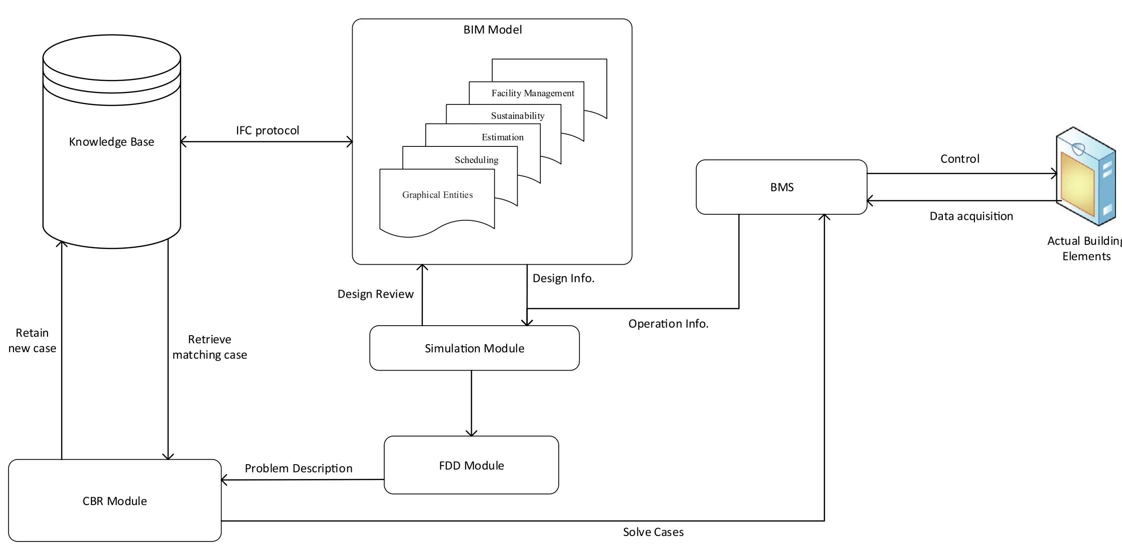

Fig. 3. BIM-IKBMS modules.

Table 9
BIM role players and their responsibilities.

Roles	Responsibility	Reference
BIM Modeller	Create & develop BIM models and extract relevant 2D/3D data/documentation	[119,123–128]
BIM Analyst	Simulate and analyse various factors based on the developed model e.g. building performance analysis, circulation, security, etc	[110,129–137]
BIM Application Developer	Develop and customize software to support integration and synergy for the BIM process form small plug-ins to BIM servers	[43,119,138]
Modelling Specialist	Contribute to the exchange of information under IFC standards considering initial requirement of IFC extensions	[119,129,139]
BIM Facilitator	Assist other professionals involved in the project to get familiar with the BIM tools and visualize the model information	[110,119,132,135]
BIM Consultant	Direct/guide various stakeholders involved in the project (e.g. designers, developers, builders) with less experience/exposure to BIM tools and the developed BIM model	[119,140]
BIM Researcher	Lead the development of new technologies to benefit the AEC industry	[119,141,142]
BIM Manager	Manage people in the implementation and maintenance of the BIM process	[119,143–145]

5.6. Effectiveness and cost barriers of proposed maintenance systems

The review has shown that BIM based systems are widely used throughout the building lifecycle and largely increase the productivity of the construction industry. It has also reviewed the current BAS and BMS and promoted the automation for construction management. Particularly, this article has discussed the nonlinear method for operations that largely improves the quality of control, and discussed how tools such as 3D TLS, RFID, etc. largely improved the availability of post-construction inspection. The proposed systems utilize previous information to achieve process efficiency. Therefore, the proposed systems perform utilizations in building energy inspections and could be an effective way to reduce building energy consumption.

However, the change of work mode for the proposed systems would cause cost barriers. Moreover, one of the main cost barrier might be caused by changing the culture of an organization. Introducing BIM technology might change the culture of an organization. Well-skilled BIM engineers would be needed initially to start the BIM project. Table 9 shows the responsibility for 8 different roles involved in the BIM process [119]. These BIM role players must solve various problems to develop effective execution plans for implementations in each role [120]. BIM model management also becomes necessary to enhance the effectiveness of the overall process [121,122].

However, it is indicated that the high costs for adapting BIM including new hardware, new software and BIM training can be prohibitive for Small and Medium Enterprises (SMEs) to invest in [146]. In addition, BIM role playing staff are required to be involved in full-time training and would therefore be absence for their routine duties for a certain period of time [23]. Revit ROI White Paper expresses that the cost of hardware and software for a BIM system is normally $6,000 while the training time might cost 3 months for an engineer with a monthly labor cost of $4,200 [147]. Moreover, the outcomes of BIM training have always been questioned [148]. Most specifically, in case a project involving BIM would not be immediately available in real-world practice, the trainees have been reported to gradually forget their learnt BIM skills [149]. This may cause firms to allocate additional funding for repeated trainings. Additionally due to the current stage of BIM development, employing professional BIM experts would be expensive [150] and the correct professional knowledge in certain fields cannot be guaranteed. BIM experts should be knowledgeable in both software and project delivery [151] otherwise, the value of BIM will become overrated as its use in various projects continues [152,153].

Applying BIM technologies can also add extra responsibilities and liabilities for the designer, therefore increasing the design fees [64]. Especially, with the requirements of nD BIM-IKBMS, BIM models should integrate more information for operation and maintenance forcing the designers to spend more time [29]. Finally, the cost for BIM-IKBMS R & D may potentially be high during the early stages. Errors caused by early immature systems and incorrect operations are also considered as BIM-IKBMS initial development risks.

6. Conclusions

This study has reviewed the current state of the art for the building energy efficiency field. As post-construction energy consumption accounts for a high proportion to total energy consumption, the energy conservation of AEC/FM industry cannot be emphasized more. The building construction LCA approach should be used to control energy efficiency. The post-construction energy consumption mainly comes from the operation of the faculty. Thus, meaningful early decision making for sustainability, timely maintenance and accurate occupant operations are three ways to reduce energy consumption. As a key factor in building design and retrofit evaluation, occupant behavior is usually oversimplified, which might cause higher deviation in LCA. To make certain evaluation for occupant behavior, this article has reviewed the uncertainties in real-world occupant behavior, including aleatory uncertainties and systemic uncertainties. Aleatory uncertainties include occupant, appliance operation and window/shading operation, while systemic uncertainties include accuracy of analysis tools, the authority of data collected and the rationality of model simplification. In confronting these uncertainties, possible simulations have been developed including pre-construction simulations which support early decision making, and post-construction simulations which promotes the process of evaluation. The aim of conventional method is to maximize the building energy efficiency while maintaining the comfort of the occupant. A 3-step process has been suggested for the energy-efficiency maximization, including, constraint's setting, tradeoff consideration and validation. After comprehensively considering these aspects, this study concludes that particular technologies for energy efficiency are required to be integrated, standardized and interacted in real time dynamics.

This study went on to review the current conditions of BIM and validated its potential in the AEC/FM industry. By adoption of BIM, energy consumption can be reduced during post-construction phase by using its advantages in comparison to the traditional CAD method. With 3-nd BIM models, rich information can be integrated and structured as 3D entities, schedules, estimation, sustainability and FM. Thus, BIM can be further developed with particular technologies such as passive RFID tags, 3D scanning, cloud computing to advance its adoption and achievements. After detailed discussion on these aspects, this article suggests that BIM has great potential in effective visualization, informatization, standardization, and collaboration in the post-construction phase. However, this study confirms that current BIM is not discipline-oriented enough for the lack of experiential multi-discipline experts and not an integrated as expected for the immature interfaces. Thus, making discipline-oriented development, especially for building energy conservation, would largely extend the use of BIM, and promote building energy efficiency. Meanwhile, an integrated BIM platform and particular advanced approaches would help conventional method of building energy conservation become integrated, standardized and dynamic.

Finally, BIM-IKBMS was proposed and reviewed. The value of BIM in both pre-construction and post-construction management has been validated by this article. The current state of the art of BMS has been reviewed and the feasibility of certain BMS and BAS that can support the development of the proposed system has also been validated. Particularly, a fuzzy logic BIM based BMS has been reviewed facing to uncertainties of occupant behavior. Concerning data collection, inspection technologies such as RFID, UWB, GNSS, 2D imaging, Photogrammetry and 3D TLS have been reviewed. These technologies can largely improve the automation of the proposed system. In terms of building maintenance, knowledge-based method can help the proposed system utilize previous information to achieve process efficiency. Above all, this platform has shown clear advantages in automation, productivity, efficiency, availability and quality and expected to efficiently reduce building energy. However, several of these advantages are theoretical, cost barriers and weakness in automation should be improved in the future.

Above all, this study focuses on reviewing the state of the art of nD BIM-IKBMS relevant technologies based on grounded theory. In the course of this analysis, this study has demonstrated that by adoption of nD BIM, the knowledge-based building management system can be applied in building energy inspections for reducing building energy consumption. Such research has established a technical basis for developing nD BIM-IKBMS. Technical feasibility of each sub technology has been validated by reviewing the latest applications. The scope of research and development for nD BIM-IKBMS can be developed, which will be used in the next step. The futuristic research is the development of nD BIM-IKBMS and validation for integration of all these technologies in an actual building project.

Acknowledgments

Authors from Ryerson University would like to acknowledge the support by the National Sciences and Engineering Research Council of Canada.

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