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Review

Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach

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ABSTRACT

Building Information Modeling (BIM) has been recognized as an emerging technological innovation which can help transform the construction industry and it has been adopted broadly in the field of built environment. Due to the rapid development of BIM research, various stakeholders require a state-of-the-art review of the BIM research and implementation. The purpose of this paper is to provide an objective and accurate summary of BIM knowledge using 1874 published BIM-related papers. The results show that 60 key research areas, such as information systems, 3D modeling, design and sustainability and 10 key research clusters, such as architecture design studio, building information and lean construction, are extremely important for the development of BIM knowledge. The results are useful for the identification of research clusters and topics in the BIM community. More importantly, these results can help highlight how BIM-related research evolves over time, thus greatly contributing to understanding the underlying structure of BIM. This study offers useful and new insights to summarize the status quo of BIM knowledge and can be used as a dynamic platform to integrate future BIM developments.

1. Introduction

The core function of Building Information Modeling (BIM) is to provide users with the ability to integrate, analyze, simulate and visualize the geometric or non-geometric information of a facility. The concept was first raised by Eastman in 1975 [1]. The terms: 'Building Information Model' and 'Building Information Modeling' (which refer to modeling building information, such as ontology development), were first used in Van Nederveen and Tolman [2] and Tolman [3]. However, much attention was paid to BIM in 2002 when it was commercially promoted by Autodesk as the process for generating and managing a facility with physical and functional information. Due to its potential benefits to enhance the information visualization, integration, interaction, sharing and communication, BIM has been widely adopted in many multi-disciplinary fields, including social (e.g. education, management and economics), natural (e.g. environmental science, ecology and energy) and computer science (e.g. information and communication technology, semantics and interoperability). Although a widespread adoption of BIM can demonstrate the usefulness of this technological innovation in multi-disciplinary fields, it can also indicate that the development and adoption of BIM may be fragmented.

The development and application of BIM in multi-disciplinary research can also be reflected in scientific literature. For example, Volk et al. [4] found that previous studies on the use of BIM in existing buildings can be categorized into four groups: functional issues, informational and interoperability issues, technical issues, as well as organization and legal issues. In order to uncover possible connections with scientific literature, many studies have been conducted to review past developments and propose new research trends for BIM. For example, Jung and Joo [5] reviewed the concepts of computer-integrated construction and BIM to provide a BIM framework for practical implementation. Cerovsek [6] examined the development of building product modeling and provided a methodological framework to improve BIM tools and schemata. Similarly, Tang et al. [7] used a critical review to identify the techniques that can be adopted to achieve automatic reconstruction of as-built building information models from laser scanning. Although many studies have been initiated, it should be noted that these reviews are typically qualitative, subjective, and based on a manual review, which can be biased and limited in terms of the number of articles that can be reviewed [8].

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In order to address the issues brought about by manual review, various structured analysis tools have been developed in recent years. These studies aim to reveal the hidden connections of various knowledge domains, which is critically important to the development of BIM, by addressing gaps in the literature and proposing new studies which are distinct enough from existing work to make a viable contribution [9]. For example, Yalcinkaya and Singh [8] used the latent semantic analysis to reorganize the unstructured data objects in the BIM literature to identify patterns for the discovery of knowledge. However, it should be noted that the latent semantic analysis relies on interrelations between different groups and the results may not be easily interpreted by readers. Many other visual tools have therefore been developed to create informative conceptualizations. These tools include Bibexcel, Sci2, VantagePoint, and CiteSpace [10], which are all supported by bibliometric techniques, such as document co-citation analysis and keyword co-occurrence analysis [11]. These techniques are based on the bibliographic records of each scientific document and can be applied to explore the unheeded linkages. As BIM can be considered interdisciplinary, an analysis of its scientific literature and associated bibliographic connections remains difficult. For example, Yalcinkaya and Singh [8] reviewed the trends in BIM by retrieving numerous thematic words from the literature using latent semantic analysis. This does not outline the connections, evolution, and growth of BIM topics in scientific literature. Similarly, He et al. [12] used CiteSpace to map the managerial areas of BIM and eight clusters, including collaboration, innovation, stakeholder, visualization, implementation, culture, framework, as well as operation and maintenance, have been identified. However, it only covers the managerial studies of BIM and only includes a limited number of studies. It should be noted that the bibliometric approach is not designed to replace a manual review. Instead, the approach can help reveal unbiased, quantitative and accurate connections between various studies. Manual reviews and insights produced by experts are still valuable for discussing, interpreting and understanding the complex subject.

In order to facilitate the development and implementation of BIM, this study aims to: 1) explore the knowledge base (e.g. unstructured key research topics) and knowledge domains (structured key research areas) associated with BIM using co-citation, co-occurrence and visualization tools based on studies from 2004 to 2015; 2) identify the evolution (e.g. the thematic flow) of BIM knowledge using citation burst detection; and 3) propose a BIM knowledge map based on the knowledge base, knowledge domains and evolution of BIM knowledge. Although this study is not an exhaustive analysis of all BIM-related literature, given its sample size, it offers a quantitative summary of the status quo of the BIM knowledge and illustrates the use of bibliometric techniques for exploring knowledge domains and hidden connections within the BIM discipline. In this study, BIM is considered as the process of generating and managing a facility with physical and functional information.

2. Background

Knowledge development is a dynamic process that often encourages particular research fields. Construction informatics is an example of the interdisciplinary field derived from both construction and computer science, shaped by a hierarchy of core knowledge and support themes [13]. BIM, as an area in construction informatics, has a similar hierarchical structure, including core areas (e.g. technical structure and information management process) and support areas (e.g. knowledge transfer, training, and education) [14]. In the field of BIM, many subareas have formed in the past few years, ranging from policy to process and technology [15]. Since its inception in 1975, most scholars tend to concentrate on one or two specific themes under a BIM sub-area that can eventually contribute to the whole body of knowledge. For example, there are studies focusing on the themes of BIM-related policy. Cheng and Lu [16] reviewed the BIM standards and policies that are available in the public sector. Howard and Björk [17] also reviewed the standards of BIM deployment and found that standards are generally supported although not applied rigorously. Dossick and Neff [18] examined BIM from an organizational point of view and concluded that although BIM fosters collaboration among project members, it does not strengthen collaboration between different organizations. In addition, Fan [19] examined intellectual property rights in BIM and concluded that ownership of the copyright of the final BIM model and model elements are both valuable.

Similarly, in the area of BIM-related processes, there are many separate studies which cover the use of BIM in various construction or project processes. For example, Lee et al. [20] proposed an ontological inference procedure to automate the method for searching work items in the tiling process. Park et al. [21] adopted a BIM approach for construction defect management, which is related to the quality control of construction processes. Kim et al. [22] relied on 3D data obtained from remote-sensing technology and developed a 4D BIM platform for automatic construction progress measurement. Similarly, Irizarry et al. [23] used BIM and Geographic information system (GIS) to track supply chain and provided necessary warnings related to the delivery of materials. It seems that BIM is a digital and capable platform to host the development and testing of various innovative theories related to construction and project processes.

As BIM is considered as an information technology enabled platform which can integrate inter-disciplinary collaboration, a few major developments have been conducted on the improvement of the platform, including information retrieval, visualization, data exchange, interaction, and interoperability. For example, Yeh et al. [24] focused on the transformation of the information from BIM models to on-site devices to ensure that correct information can be retrieved with minimal effort. Yan et al. [25] improved the design process in a BIM environment to enhance architectural design and visualization. Jeong et al. [26] investigated data exchange between various BIM models and confirmed that much work is still needed to achieve full interoperability between various BIM platforms. This is in accordance with Grilo and Jardim-Goncalves [27] who found that interoperability remains challenging and an investigation of interoperability at the business level, along with the technical level, is also needed.

It should be noted that although some studies are the fundamental building blocks, others may simply be practical applications or implementations of BIM, which add limited value to the growth of BIM knowledge. In order to identify the fundamental building blocks of BIM knowledge and their connections, there are many reviews which have been conducted. However, the collection of BIM knowledge in literature is extensive, and the ability to investigate connections and relationships among authors, articles, journals, publication dates, or geographic regions remains difficult. As such, many previous reviews only use a manual review method and may have a high level of bias. For example, Wong and Zhou [28] reviewed the use of BIM in enhancing sustainability and found that the current fundamental barriers against green BIM are during its implementation in the design and construction stages. Similarly, Bradley et al. [29] used a critical review to investigate the use of BIM for infrastructure and found that ICT system development and the modeling of infrastructure projects are the fundamental pillars in the research area. Tang et al. [7] conducted reviews to survey the adoption of laser-scanned point clouds for BIM's creation and found that filling the gaps among existing promising techniques and algorithms could become a fundamental burst for automated as-built BIM creation. Despite the importance of identifying fundamental building blocks of BIM knowledge, few studies have been conducted on BIM in a broader context.

Scientific literature contains both persistent and transient elements [30]. The persistent aspect of science literature can be characterized as knowledge domains which are the structured representation of unstructured data and can be identified through clustering analysis. In addition, the transient aspect of scientific literature can be characterized as a knowledge evolution pattern, which can be identified by citation burst detection [31]. With recent advances in computing technology, scientific indexes, and information visualization techniques, researchers are able to discover the hidden connections and trends in the literature. For example, co-citation analysis, which is a semantic similarity that extracts relationships between documents and authors, has been adopted by a variety of researchers to map and study the knowledge structure. These quantitative analysis tools, combined with the visualization tools, can improve the understanding of the knowledge, especially the dynamics of underlying themes [32]. Meanwhile, a systematic exploration of the knowledge domains will benefit the establishment of a scientific theory in BIM by identifying the key foundations that BIM knowledge stands on.

3. Research method

In this study, two datasets of bibliographic records on 'Building Information Modeling (BIM)' are retrieved from the Web of Science (WoS) using a topic search and a subsequent expansion search through citation links. The topic search dataset is referred to as the core dataset. The expanded dataset represents a broader context of the core. Key findings, including the identification of the knowledge domains and knowledge base, are based on the core dataset. The identification of the evolution pattern of the BIM knowledge through citation burst detection is based on the expanded dataset. This strategy is also adopted by many previous studies, such as Chen et al. [33] and Chen et al. [34].

3.1. Data collection

3.1.1. Bibliographic records

Each bibliographic record contains the metadata of a published article, including a list of authors, the title, the abstract, a set of keywords and a set of references cited by the article. Each reference contains the first author's name, year of publication, source type (e.g., journals, conference proceedings, book series, books, etc.), volume number and DOI reference. Using the DOI reference, the reader can access the full text of the corresponding article.

3.1.2. The core dataset

The core dataset is retrieved by a topic search in the WoS™ Core Collection. Two keywords, which are Building Information Model* and BIM are used for the topic search. The wildcard character * is used to capture relevant variations of a word, such as Building Information Model, Building Information Modeling, and Building Information Modeling. The abbreviation 'BIM' is used to exclude the records which are only within the themes on building, information and model* separately. Articles which include the two keywords in the Title/Abstract/Keywords (T/A/K) are selected. The search shows 938 records of original research articles, reviews and proceedings papers from 2004 to 2015.

3.1.3. The expanded dataset

The expanded dataset includes extra records obtained by the citation links from the articles in the core dataset. Although articles may not contain any of the BIM related terms, they may cite at least one article in the core set. As such, it is reasonable to assume that it may be thematically relevant to the core dataset. This citation expansion method originates from the principle of citation index by Garfield and Sher [35]. In the citation report of WoS, the core dataset is cited by 936 records. These records are merged into the core dataset to get the expanded dataset which consists of 1874 records. The bibliometric approach adopted in this study is based on both datasets shown in Table 1.

3.2. Data analysis

3.2.1. Bibliographic map of BIM

The bibliographic map of the BIM can be represented by a network of various entities such as collaborating authors, cited references and co-occurring keywords. CiteSpace supports the construction of several types of networks from bibliographic sources. This study focuses on a keywords co-occurrence network and a document co-citation network. These two techniques are advantageous over the conventional manual review method. Compared to the conventional method, a more extensive and more diverse range of related topics can be investigated. In addition, such techniques can be applied to modify the reviews as often as needed as the research progresses, while individuals may not have ample capacity to conduct critical manual review quite so frequently.

The keyword co-occurrence network is employed to detect "keywords" that co-occur in at least two different articles in a time span. Therefore, keywords with high frequency and centrality can be identified as indicators of critical research focuses or directions in a time period [36]. These keywords are considered as the knowledge base of BIM.

Document co-citation analysis evaluates the network created when documents are linked according to their joint citations by subsequent documents. Frequently cited documents are likely to have a greater influence on the discipline than those less cited [32]. If two documents are frequently jointly cited, they are likely to share similar or related concepts. By counting and analyzing the frequency of two documents cited in the same research, one can identify groups of closely related documents which address the same research domains [32]. A link in a document co-citation network represents how frequently two articles are cited together by other articles in a dataset such as the core and expanded datasets. Individual nodes in the network can be aggregated into groups, or clusters, based on their interconnectivity. Each cluster represents a distinct domain. CiteSpace is designed to synthesize and visualize a time series of individual networks extracted from each year's publications. Using CiteSpace, the whole network can be divided into clusters, e.g., groups of entities. Entities within the same cluster are more similar to each other than entities from other clusters. The homogeneity of each group is measured by a silhouette score from -1 to 1, where a high value indicates that the object is well matched to its own cluster and poorly matched to neighboring clusters. The quality of the overall division is measured by the modularity measure.

3.2.2. The evolution of BIM knowledge

CiteSpace can also help identify highly cited landmark articles, articles with strong citation bursts and keywords with a strong surge on citation frequency. The goal of burst detection is to determine whether the appearance of an entity increases sharply when compared with its peers. If an article is found to have a sharp increase in citation counts, the article can be considered to have a citation burst. A citation burst indicates an increased attention to the underlying work, which can then be considered as a milestone in the evolution of BIM knowledge.

4. Results

4.1. The knowledge domain in the core dataset

4.1.1. Document co-citation analysis

Fig. 1 shows the overview of the document co-citation network generated from the core dataset with 230 nodes and 701 links, visualized and analyzed by the CiteSpace. As can be seen from Fig. 1, CiteSpace divides the timeline (2004–2015) into a series of time slices (each time slice equals one year). The top-cited publications (top 50 publications) during each time slice are selected for subsequent analysis. Nodes represent cited reference in the core dataset, and the links connecting nodes represent co-citation relationships. To facilitate easy interpretation, the color of links corresponds directly to each time slice.

Table 1
The core and expanded datasets included in this study.

Dataset	Duration	Results	Articles	Reviews	Proceedings	Authors	Institutions
Core	2004–2015	938	433	14	498	1833	613
Expanded	2004–2015	1874	1118	63	705	4126	1360

For example, sky blue links describe two publications that are co-cited in 2007 and orange links connect publications that are co-cited in 2015. In addition, larger node size suggests that the publication is cited more frequently and implies that the paper is an important one in BIM knowledge.

Based on Fig. 1, the top ten cited publications from 2004 to 2015, including two editions of the book and nine journal articles, are shown in Table 2. The first two are the two editions of the BIM Handbook [37] which serve as an introduction of BIM for professionals and researchers from varied disciplines. These two editions of the BIM Handbook are essential resources in the BIM discipline. Although the majority of documents citing these two editions of the Handbook are journal articles, which is contrary to the citation habit of many disciplines [38], this is not uncommon for BIM because these two editions of the Handbook contain fundamental conceptual and methodological knowledge that is discipline unspecific (e.g., can be easily borrowed and implemented by other fields). The other nine journal papers are mostly review-oriented, focusing on particular BIM implementation and adoption in the AEC industry. For example, Succar [15] explored some of the publicly available international guidelines and introduced the BIM framework, which is a research and delivery foundation for industry stakeholders. Howard and Björk [17] conducted a qualitative study based on information from a number of international experts and asked a series of questions about the feasibility of BIM (which refer to the files which can be retrieved, extracted, exchanged or networked to support decision-making regarding a facility), the conditions for BIM success, and the role of standards with particular reference to the International Foundation Classes (IFCs).

In summary, regardless of the specific research area, all ten publications consider BIM as a key technology for pursuing specific research objectives related to the life cycle of a facility from physical or social aspects. It is also interesting to observe that the cited frequency generated by CiteSpace may be different from the citations produced by Google Scholar or WoS. For example, Gu and London [39] investigated the understanding and facilitation of BIM in the AEC industry and has been cited more than 327 times on Google Scholar and more than 90 times on WoS at the time of the study. However, the cited frequency produced by CiteSpace is 37 citations. Although this may seem like a significant difference in the number of citations, it should be noted that there are circumstances when BIM-related studies are cited by reports which are not relevant to BIM. As discussed earlier, all publications are retrieved by searching a phrase of “Building Information Model*” and a word “BIM” in the Title/Abstract/Keywords. This strategy can ensure that meaningful citations (i.e. citations which contribute to the development of BIM knowledge) are identified.

4.1.2. *Cluster identification and interpretation (knowledge domains)*

The identification of key publications (e.g., nodes) through document co-citation analysis is an essential step in determining a knowledge domain. The second phase of the study is to investigate clusters of publications to identify patterns and trends in the body of knowledge. Cluster labels are selected from the noun phrases of each cluster and noun phrases are extracted from titles, keywords, and abstracts of the publications. Top-ranked noun phrases then become candidates for

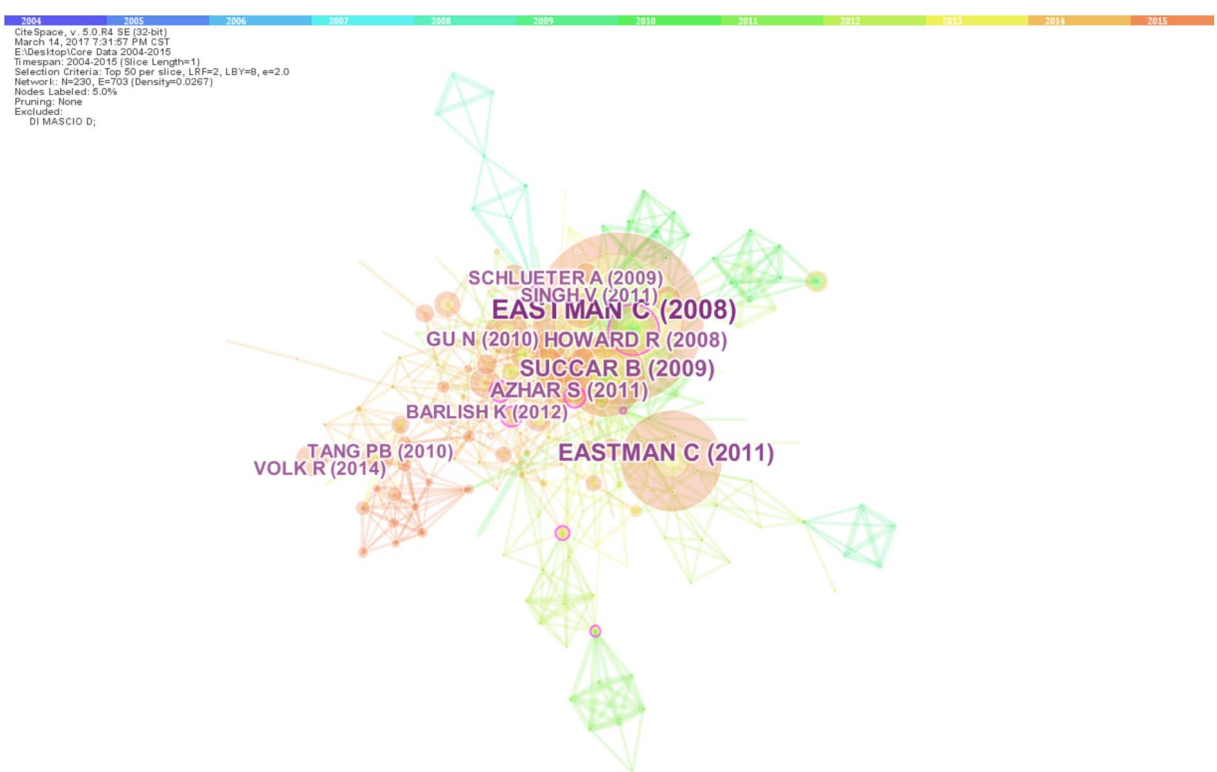


Fig. 1. Document co-citation network of BIM studies.

Table 2
The top ten critical publications in the BIM discipline.

Author	Title	Year	Cited frequency	Document type
Eastman CM, Teicholz P, Sacks R, Liston K	A guide to building information modeling for owners, managers, architects, engineers, contractors, and fabricators.	2011	232	Book
Succar, B.	Building information modeling framework: A research and delivery foundation for industry stakeholders.	2009	72	Automation in construction
Howard, R., & Björk, B. C.	Building information modeling–Experts' views on standardisation and industry deployment	2008	45	Advanced Engineering Informatics
Azhar, S.	Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry	2011	43	Leadership and Management in Engineering
Gu, N., & London, K.	Understanding and facilitating BIM adoption in the AEC industry.	2010	37	Automation in construction
Singh, V., Gu, N., & Wang, X.	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	2011	32	Automation in construction
Barlish, K., & Sullivan, K.	How to measure the benefits of BIM-A case study approach	2012	29	Automation in construction
Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A.	Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques	2010	29	Automation in construction
Volk, R., Stengel, J., & Schultmann, F.	Building Information Modeling (BIM) for existing buildings - literature review and future needs	2014	28	Automation in construction
Schlueter, A., & Thesseling, F.	Building Information Model Based Energy/exergy Performance Assessment in Early Design Stages	2009	28	Automation in construction

cluster labels.

Three statistical methods including the log-likelihood ratio (LLR) test [40], term frequency-inverse document frequency (TF∗IDF) [41] and mutual information (MI) tests are used for this process.

- An LLR test is a statistical test used to compare two models' goodness of fit on the basis of the likelihood ratio. The LLR is calculated by comparing the likelihood of finding a term in one cluster against the likelihood of finding exactly the same term in another cluster. It is useful to identify the uniqueness of the term to a cluster [32].
- TF∗IDF, as a numerical metric to reflect how relevant a word is to a text, and MI tests, as a measure of mutual dependence between two random variables, are also applied to represent the most salient aspect of the clusters [32].

Fig. 2 shows the labeled clusters with abstract terms and their relative importance via an LLR test (with the largest cluster numbered as #0 and the smallest cluster numbered as #9). The size of a cluster is decided by the total number of publications that the cluster contains. Table 3, exported from CiteSpace, specifies the largest 10 clusters in rank order. The silhouette value of each cluster is greater than 0.65, suggesting robust and meaningful results.

It is interesting to find that the clusters of building information, augmented reality, architectural design studio and lean construction are connected to each other within the network and are linked by various nodes (i.e. publications).

The most significant cluster is the architectural design studio, which includes 27 articles. These studies are related to facility design, covering parametric design, sustainable design, design for safety and

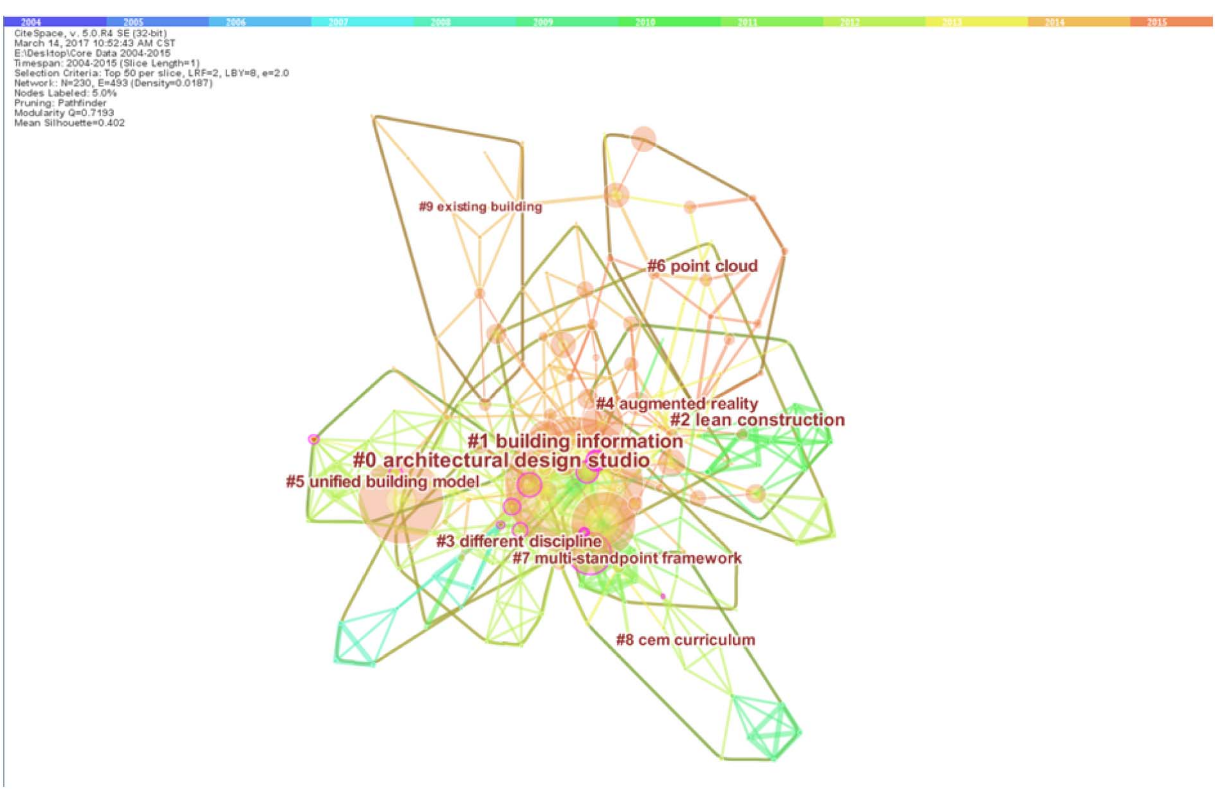


Fig. 2. Clusters of knowledge domains within the BIM discipline.

Table 3
Top-ranked clusters and the terms within the clusters.

ID	Size	Silhouette	Label (LLR) (*p*-value)	Label (TF*IDF)	Label (MI)	Mean (cited year)
0	27	0.719	Architectural design studio (2919.38, 1.0E − 4)	Design	Collaborative working	2008
1	26	0.678	Building information (2270.88, 1.0E − 4)	Rich semantic information	Industry foundation classes (IFC)	2010
2	18	0.869	Lean construction (1394.51, 1.0E − 4)	Lean production management system	Industrialized construction	2007
3	16	0.761	Different discipline (1307.27, 1.0E − 4)	BIM adoption	BIM implementation	2008
4	16	0.895	Augmented reality (3557.33, 1.0E − 4)	Defect	Information retrieval and visualization	2008
5	16	0.76	Unified building model (3044.76, 1.0E − 4)	3d geo-information system	Integration of BIM and GI (geo-information)	2008
6	16	0.879	Point cloud (5257.62, 1.0E − 4)	Automated 3d modeling	As built data collection and modeling	2010
7	15	0.771	Multi-standpoint framework (2908.92, 1.0E − 4)	Stakeholder	Decision making	2007
8	15	0.854	CEM curriculum (3492.71, 1.0E − 4)	Learning effect	Pedagogy	2008
9	11	0.78	existing building (2232.36, 1.0E − 4)	Facility management	Sustainability	2009

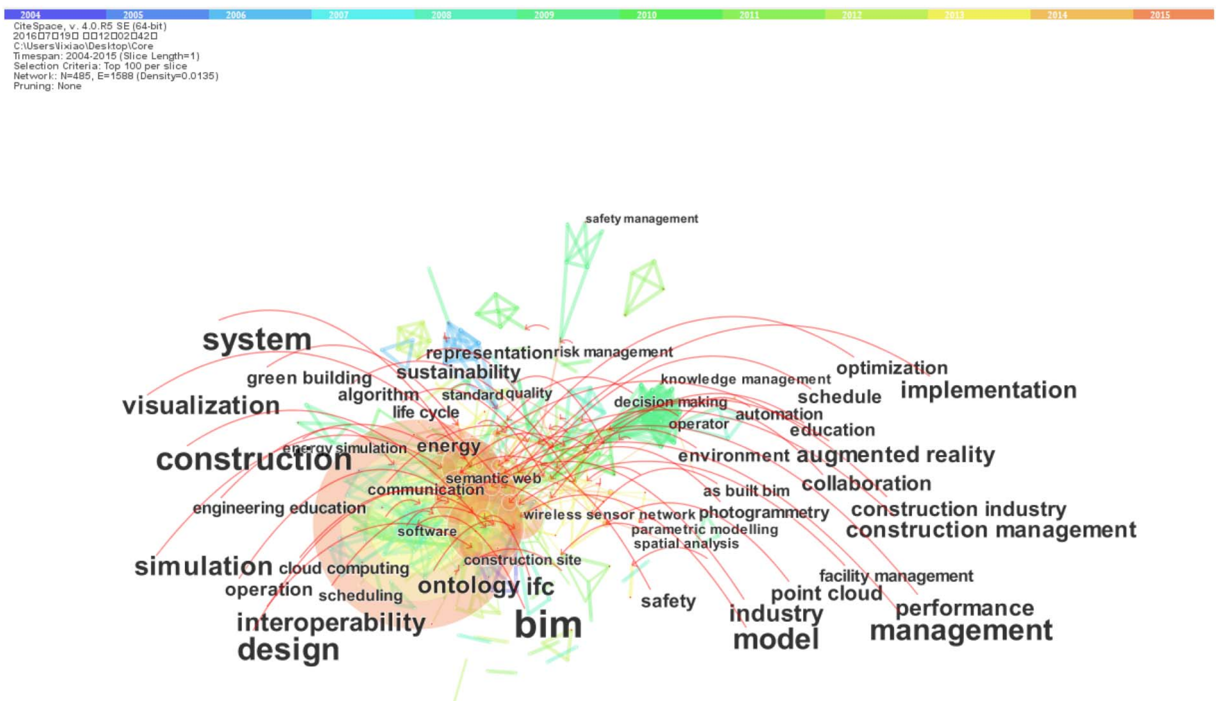


Fig. 3. Keywords co-occurrence network.

constructability, as well as collaborative working. In accordance with Turk et al. [42] and the Cumulative Index of computer-aided architectural design (CUMINCAD), which is a digital library for scientific information of CAAD [43], it has been found that "design" and "collaborative working" are the two key terms in this cluster when analyzed by the TF*IDF and MI clustering algorithms. It appears that researchers are interested in optimizing the design process and outputs, by improving parametric design, sustainable design, design for safety and constructability, and are also concerned about improving collaborative working among different disciplines. The result indicates that computer-aided architectural design (CAAD) has been evolving from producing design/construction drawings (i.e. traditional CAD drawings) to facilitating design plan decision-making and collaboration of AEC/FM industry teams [44], which can enhance the capacity of representation, situatedness, integration, and communication of a design platform [45]. In addition, this cluster covers the early stages of the life-cycle of a building, reflecting the importance of the design stage in BIM knowledge. However, one interesting finding is that CAAD education and architectural education, which were previously identified as one of the largest clusters in Turk et al. [42], are not identified as key terms within this cluster. This may suggest that BIM education has gradually improved over the years and the gap between the industry requirements and BIM courses is being minimized, although many challenges related to BIM education can still be identified [46].

The second most significant cluster is related to building information. The studies are related to the information exchange among heterogeneous BIM tools, applications, and systems. The standardized and re-usable model view definitions (MVDs) can be adopted to support industry foundation classes (IFC) data schema to improve information interoperability, particularly semantics information. It is worth mentioning that most of the articles in this cluster are published between 2004 and 2015, indicating that this cluster is an emerging core component of BIM knowledge.

Another main cluster is lean construction, which targets at smoothing the construction and information flow, thereby minimizing variation, the waste of material, time and human resources. The studies are related to lean principles (e.g. constraints management, pull method, Just-in-time), work process simulation, and workspace analysis. BIM plays a significant role in managing the information and visualizing the work process for lean construction. In addition, as demonstrated by the MI results, industrialized construction, including prefabricated construction, modular construction, and precast construction, also contributes to BIM and lean construction for enhancing construction planning and control. It should be noted that lean

Table 4
Top keywords with their frequency in BIM.

Frequency	Keywords	Frequency	Keywords
731	BIM/BIMs	14	Quality Control/ Inspection
321	Construction/Industry/AEC	14	Case Study
148	System/Information System	13	Optimization
112	3D/nD Modeling Application	13	Site Layout
100	Design (e.g. Parametric/ Rule-based)	12	Innovation
68	Software	11	Risk Management
65	Green Building/ Sustainability/Energy	11	As Built BIM
55	Industry Foundation Classes/IFC	11	Automation
51	Interoperability/Data Exchange	10	Representation
44	Simulation	9	Photogrammetry
42	Laser Scanning/Point Cloud	9	Cloud Computing
39	Visualization	8	Wireless Sensor Network
34	Geographic Information (GI)	8	Communication
33	Implementation/Adoption	7	Precast Concrete
33	Cost Control	7	Semantic Web
33	Augmented Reality/Virtual Reality	7	Decision Making
30	Facility Management	7	Lean Construction
27	Performance	6	Cultural Heritage
27	Life Cycle Management	6	Indoor Navigation
27	Ontology	6	Information Retrieval
25	Knowledge Management	6	Behavior
25	Collaboration	5	Benefit
23	Engineering Education	4	BIM Server
22	Algorithm	4	Infrastructure
19	Scheduling	4	Model View Definition
17	Operation/Operator	4	Pedagogy
17	integration/segmentation	3	Maturity Model
16	Safety Management	3	Information Delivery Manual
15	Standard	3	Mega Project
15	Spatial Analysis	3	Web3D

construction originates from the Toyota Production System (TPS) which is a production planning and control approach. As such, the production-based characteristics of industrialized construction are an essential component of lean construction.

4.1.3. Keyword co-occurrence network (knowledge base)

Since keywords are related to the core content of the publications, an analysis of keywords can help identify critical research topics in BIM-related studies. A standardisation process is adopted to group similar terms. For example, "BIM," "building information modeling," "building information modeling," or "building information models," "BIM technology" are identified as "BIM/BIMs." Fig. 3 shows the overview of the keyword co-occurrence network generated from the core dataset with 485 nodes and 1588 links. A node represents one key term identified from publications. The size of each node is proportional to the co-occurrence frequencies of the related keywords. Table 4 lists the top 60 terms with a total of 2442 co-occurrence frequencies, which account for more than 90% of all keyword frequencies.

As can be seen from Fig. 3 and Table 4, the most frequently used terms are BIM/BIMs with 731 times and Construction (construction management) with 321 times. System/information system and 3D/nD modeling application are the second largest hotspots in BIM-related research, appearing 148 and 112 times respectively. Therefore, it can be reasonably concluded that the information system and 3D/nD modeling application are the basic components in BIM research. The term "Design" is the third largest hotspot with 100 occurrences. BIM is first applied in the design stage when it is introduced to the construction industry, including architecture design, structure analysis, MEP (mechanical, electrical, and plumbing) collision detection, sustainable design and space design. In addition, most software is developed to assist design activities. For example, Autodesk® Revit® Architecture/Structure/MEP software is a complete, discipline-specific building design and documentation system supporting all phases of design. The Autodesk® Green Building Studio® web-based energy analysis service can help architects and designers perform whole building analysis and optimize energy efficiency earlier in the design process.

Green building, sustainability, and energy simulation is another important research area, and its occurrence is 65. Given the increasing recognition of sustainability, green BIM has been advocated for its potential to support environmentally sustainable building development through integrated design information and collaboration [47,48]. Most green BIM research centers on the environmental performance of the development [49], design [47] and construction [50] stages of the building life cycle. There are also a few studies which concentrate on the development of BIM-based tools for managing environmental performance and energy simulation during building maintenance [51], retrofitting [52], and demolition stages [53].

Industry foundation classes and interoperability are critical topics for using BIM as a robust system in the life cycle of various projects. As knowledge sharing between different stakeholders in a building project has relatively high priority, IFC is important to provide a rich schema for interoperability through object-based transactions in the BIM platform. The AEC/FM industry is following the trend and is moving towards cloud-based, scalable, and ubiquitous architectures to support the model creation, data sharing, and information consumption for BIM [54].

The BIM domain and the Geographic Information System (GIS) domain share a mutual objective for better information storage, exchange, and analysis. Many studies have been centered on the integration of BIM and GIS, making geographic information an important research area in BIM. For example, Isikdag et al. [55] investigated the application of BIM in a geospatial context in order to improve information exchange and storage between the two platforms. In addition, Irizarry et al. [23] established a prototype system to integrate BIM and GIS to enable the tracking of the supply chain status. Information from the GIS platform can facilitate BIM applications such as site selection and onsite material layout, while BIM models can help generate detailed models in the GIS platform and achieve better utility management [56].

BIM implementation and adoption is also a major research topic. However, both BIM implementation and BIM diffusion are yet to be reliably assessed at the market scale [57]. BIM research shows that there is an increasing interest among practitioners and academics to assess maturity, productivity, and performance of BIM implementation. For example, Chen et al. [58] proposed a structural equation model of BIM maturity through multivariate analyses of data based on BIM-related professionals' experience to measure the extent to which BIM is explicitly defined, managed, integrated and optimized. This suggests that as BIM implementation and adoption grows, the need for BIM implementation assessment also increases in order to facilitate monitoring, measuring, and improving BIM practices [59].

The innovation on cost, schedule, safety, quality and risk management in BIM also forms an important domain. This is related to the development of multi-dimensional (nD) modeling in BIM. The nD model provides a database allowing all stakeholders to retrieve necessary information from the same system, which allows them to work cohesively and efficiently during the whole project life-cycle [60]. The database can be used to address various project requirements, including scheduling [22], costing [20], stability [61], sustainability [62], maintainability [52], evacuation simulation [63] and safety [64], each of which can be considered as one additional dimension to the traditional 3D BIM model.

The effectiveness of real-time communication within the BIM environment is somehow restrained due to the nature of BIM which is examined as virtual objects [65]. An emerging topic in BIM is to combine virtual reality and augmented reality to address low productivity in retrieving information, the tendency of committing an error in assembly, and low efficiency of defect inspection [66]. Virtual reality based simulators (either non-immersive or immersive) have been developed to provide construction managers with the opportunity to experience challenges of real-life projects through simulated scenarios [67].

The ontology of construction informatics has been developed and applied to define the field, map its structure and provide a system to organize the related knowledge (i.e. knowledge classes and hierarchy) [13]. Turk [13] argued that any scientific field, including BIM, requires a framework to organize the knowledge. As such, many recent studies have been conducted on investigating elements of BIM, their relationships and applications through ontology to solve various construction problems, including building cost estimation [20], construction defect management [21], construction safety [68] and quantity take-off [69]. As the aim of creating ontology is to facilitate communication between people and interoperability between systems [15], there is a growing focus on the integration of ontology and semantic web technology to clarify domain knowledge structurally and ease its reusability [68]. In other words, the ontology model facilitates the creation of information exchange rules and the identification of constraints for specific applications across various BIM tools and systems. Ontology-based Information Delivery Manuals (IDMs) and Model View Definitions (MVDs) to formalize the domain knowledge are some of the most recent developments under the introduction of ontology [70].

BIM education, which may include the integration of BIM into mainstream civil engineering and construction management courses, also has a relatively high frequency. Using BIM technology as an integrated format in construction education will provide students with a higher quality training on the skills and knowledge required by the industry. A rich and collaborative learning environment will be achieved through purposeful attempts at integrating BIM into various course contents [71].

Although there are numerous other clusters and keywords identified from Table 2 and Table 3, the primary aim of this analysis is to identify large clusters and their relevant keyword co-occurrences. The analysis is extracted by CiteSpace to represent most, if not all, of the main research interests in the knowledge domain of BIM. Using BIM technology, construction information, and collaborative working approaches, BIM-related research covers the fields of education, management, economics, environmental science, ecology, energy, semantics, information science, and many other research areas. As can be seen from the visualization of clusters in Fig. 2 and Fig. 3, it is apparent that BIM is an interdisciplinary domain and can influence many other research areas.

4.2. The evolution of BIM knowledge in the expanded dataset

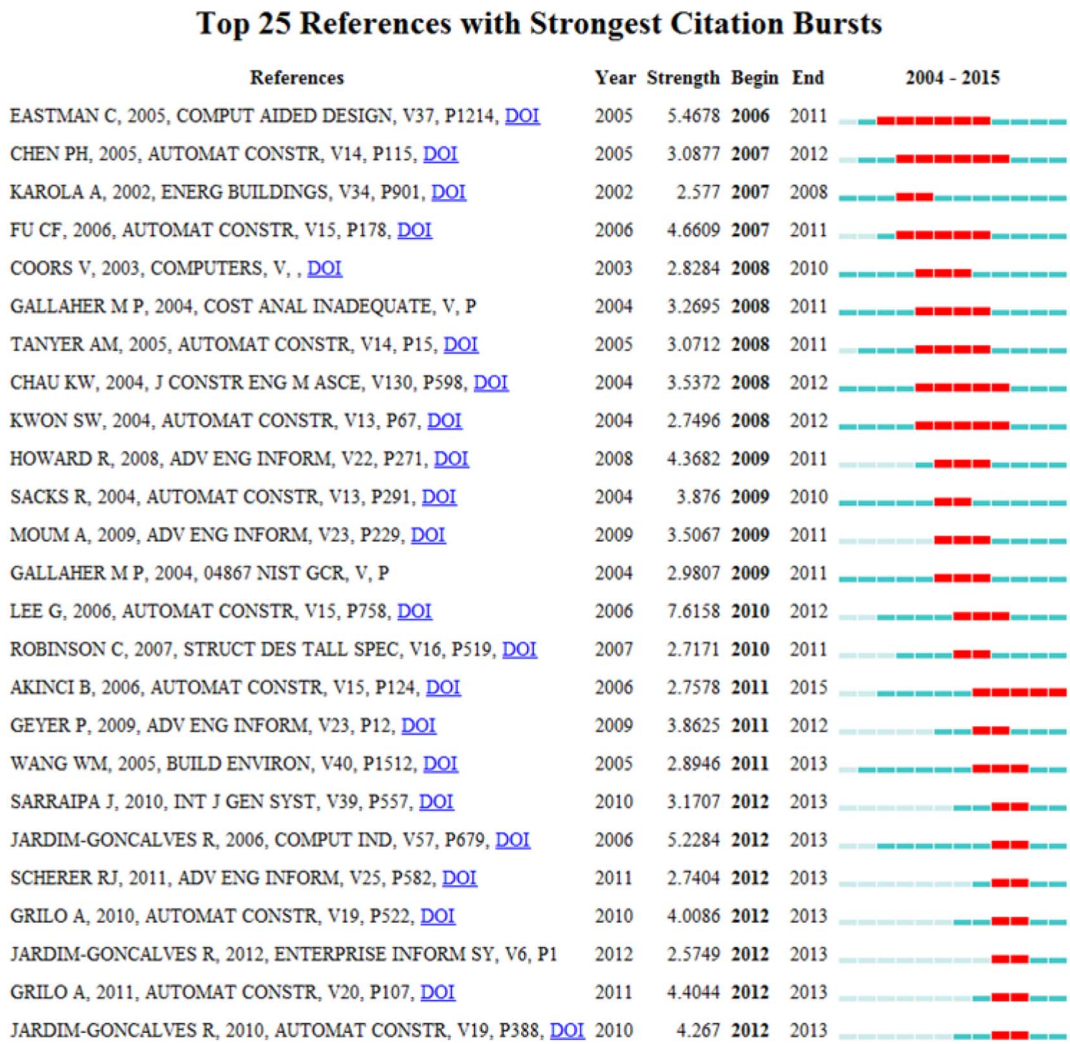
The expanded dataset, consisting of 1874 records, puts the core dataset in a broader context with contributions from a total of 4126 distinct authors from 2360 institutions. These additional records are included because they cite one or more articles in the core dataset and are useful to examine the impact of BIM in a broader context. The expanded dataset contains over 26,206 references and 30,043 keywords.

Fig. 4 shows the top 25 references with the strongest citation bursts. A citation burst indicates the likelihood that the scientific community has paid or is paying special attention towards the underlying contribution of the article. Among all citation bursts starting in 2006, the strongest burst is associated with Eastman et al. [72], which reviews the history, methods and deployment issues of CIMsteel Integration Standard, Version 2 (CIS/2) and it is an early example of a production-implemented product model, serving both bilateral exchange and object model repository implementations. A citation burst of Sacks et al. [73] is also detected from 2009 to 2010. This paper investigates technical issues associated with the use of parametric solid modeling to design buildings with construction levels of detail. The next generation of CAD, using 3D parametric building modeling with embedded assembly, piece and component function, and behavior, provides a new level of support for building design automation [73].

The bursts starting from 2007 are mainly focusing on industry foundation classes. Chen et al. [74] presented the implementation of an Industry Foundation Classes-based (IFC-based) information server for web-enabled collaborative building design between the architect and structural engineer. The Industry Foundation Classes (IFC) are adopted as the information model of the server to facilitate the interoperability among multidisciplinary AEC software applications. Fu et al. [75] presented the details of the development of an IFC viewer, which is designed to be an integrated interface for nD modeling applications. Karola et al. [76] developed a tool named BSPro COM-Server which can achieve IFC compatibility with a quite reasonable amount of work.

The bursts starting from 2008 are found to be related to Howard and Björk [17], Chau et al. [77] and a report by Gallaher et al. [78]. The strongest burst in 2008 by Howard and Björk [17] is a qualitative study about the feasibility of BIM, the conditions necessary for its success, and the role of standards with particular reference to the IFCs based on opinions from a number of international experts. This gradually leads to the development of research related to the BIM standards and adoptions. The bursts of Chau et al. [77] and Tanyer and Aouad [79] lead to a new trend of research on 4D simulation and planning. Chau et al. [77] presented a 4D visualization model that aims to help construction managers plan day-to-day activities more efficiently and also help coordinate site management activities by understanding the relevance of modern computer graphics to site management activities. Tanyer and Aouad [79] developed a 4D planning tool which brings the 4D simulation and cost estimation together and aims to contribute to what-if analysis in construction projects, e.g. what is the construction project's performance if it has varied requirements on time and cost? In addition, Gallaher et al. [78] identified and estimated the efficiency losses in the U.S. capital facilities industry caused by inadequate interoperability among computer-aided design, engineering, and software systems. The results address the cost burden issue by presenting both quantitative and qualitative findings and identifying significant opportunities for improvement. The report also analyses the barriers to improved interoperability. In addition to these citation bursts, the trends on point clouds and 3D-GIS are related to Kwon et al. [80] and Coors [81]. These two studies investigated a rapid 3D modeling approach that combines human recognition and point cloud data, and a query-oriented data model for 3D geometry and topology to enhance 3D construction site modeling and 3D-GIS data visualization respectively which are often cited by subsequent research.

Citation bursts starting during 2009 to 2011 are led by Lee et al. [82], Geyer [83] and Moum et al. [84]. The strongest citation burst in the entire expanded dataset is related to Lee et al. [82], which explored the extent to which design and engineering knowledge can be practically embedded in production software for BIM and focused on a building object behavior (BOB) description notation and method, developed as a shorthand protocol for designing, validating and sharing the design intent of parametric objects. Geyer [83] applied a performance optimization based on resource consumption extended by preference criteria to allow the designer to interact with the optimization in order to assess qualities of aesthetics, expression, and building function. In addition, the strategic level of discussion on BIM is very popular in this period. For example, Moum et al. [84] and Robinson [85] are related to developing strategies, demands, and guidelines in the digital construction using BIM. Some detailed applications of BIM revolution also have strong citation bursts. Fig. 4 shows that the areas of design [83] and green building [86] and quality [87] have strong bursts. Wang et al. [86] presented the use of an optimization program coupled with an energy simulation program, which allows the design space to be explored in the search for an optimal or near optimal



Top 25 References with Strongest Citation Bursts

References	Year	Strength	Begin	End
EASTMAN C, 2005, COMPUT AIDED DESIGN, V37, P1214, DOI	2005	5.4678	**2006**	2011
CHEN PH, 2005, AUTOMAT CONSTR, V14, P115, DOI	2005	3.0877	**2007**	2012
KAROLA A, 2002, ENERG BUILDINGS, V34, P901, DOI	2002	2.577	**2007**	2008
FU CF, 2006, AUTOMAT CONSTR, V15, P178, DOI	2006	4.6609	**2007**	2011
COORS V, 2003, COMPUTERS, V, , DOI	2003	2.8284	**2008**	2010
GALLAHER M P, 2004, COST ANAL INADEQUATE, V, P	2004	3.2695	**2008**	2011
TANYER AM, 2005, AUTOMAT CONSTR, V14, P15, DOI	2005	3.0712	**2008**	2011
CHAU KW, 2004, J CONSTR ENG M ASCE, V130, P598, DOI	2004	3.5372	**2008**	2012
KWON SW, 2004, AUTOMAT CONSTR, V13, P67, DOI	2004	2.7496	**2008**	2012
HOWARD R, 2008, ADV ENG INFORM, V22, P271, DOI	2008	4.3682	**2009**	2011
SACKS R, 2004, AUTOMAT CONSTR, V13, P291, DOI	2004	3.876	**2009**	2010
MOUM A, 2009, ADV ENG INFORM, V23, P229, DOI	2009	3.5067	**2009**	2011
GALLAHER M P, 2004, 04867 NIST GCR, V, P	2004	2.9807	**2009**	2011
LEE G, 2006, AUTOMAT CONSTR, V15, P758, DOI	2006	7.6158	**2010**	2012
ROBINSON C, 2007, STRUCT DES TALL SPEC, V16, P519, DOI	2007	2.7171	**2010**	2011
AKINCI B, 2006, AUTOMAT CONSTR, V15, P124, DOI	2006	2.7578	**2011**	2015
GEYER P, 2009, ADV ENG INFORM, V23, P12, DOI	2009	3.8625	**2011**	2012
WANG WM, 2005, BUILD ENVIRON, V40, P1512, DOI	2005	2.8946	**2011**	2013
SARRAIPA J, 2010, INT J GEN SYST, V39, P557, DOI	2010	3.1707	**2012**	2013
JARDIM-GONCALVES R, 2006, COMPUT IND, V57, P679, DOI	2006	5.2284	**2012**	2013
SCHERER RJ, 2011, ADV ENG INFORM, V25, P582, DOI	2011	2.7404	**2012**	2013
GRILO A, 2010, AUTOMAT CONSTR, V19, P522, DOI	2010	4.0086	**2012**	2013
JARDIM-GONCALVES R, 2012, ENTERPRISE INFORM SY, V6, P1	2012	2.5749	**2012**	2013
GRILO A, 2011, AUTOMAT CONSTR, V20, P107, DOI	2011	4.4044	**2012**	2013
JARDIM-GONCALVES R, 2010, AUTOMAT CONSTR, V19, P388, DOI	2010	4.267	**2012**	2013

Fig. 4. Top 25 references with strong citation bursts.

solution(s) for a predefined problem. Akinci et al. [87] outlined a process of acquiring and updating detailed design information, identifying inspection goals, inspection planning, as-built data acquisition and analysis, and defect detection and management.

The seven references which have strong citations burst from 2012 are categorized as one group because all focus on interoperability. For example, the strongest citation in interoperability is related to Grilo and Jardim-Goncalves [88], which investigated the potential value of interoperability and strategies to enhance this between computer systems and applications. Jardim-Goncalves and Grilo [89] proposed the SOA4BIM (service-oriented architecture (SOA) for BIM) framework as a cloud of services that enables universal access to the BIM paradigm by any system, application, or end user on the web [89]. Interoperability has been recognized as a problem in BIM due to the many heterogeneous applications and systems typically been used by different players, together with the dynamics and adaptability needed to operate in BIM [90]. However, despite the availability of various strategies to standardize data models and services for the AEC industry, the goal of seamless interoperability is far from being realized [91].

5. Discussion and implications

The need for a systematic and comprehensive BIM knowledge map and framework has been highlighted by many studies. For example, Succar [15] argued that BIM can be used to address various problems in the construction industry. Such high coverage highlights the necessity for a BIM framework to organize domain knowledge. According to Succar [15], BIM knowledge is organized into three fields, including policy, process, and technology. He et al. [12] summarized the managerial areas of BIM knowledge and found that there are five key research areas, including stakeholder, adoption process, conceptual framework, application approach and working environment. The major uniqueness of this study is to use a systematic and quantitative bibliometric approach for clearly visualizing and interpreting the knowledge base, knowledge domains and knowledge evolution of BIM. The findings of hidden connections among knowledge base, domains and evolution can be integrated to form the BIM knowledge map, which is shown in Fig. 5.

Fig. 5 shows that the BIM knowledge map has three major components, namely the knowledge base, knowledge domains and knowledge evolutions. The BIM knowledge base includes various separated key research topics in BIM which are identified using the keyword co-occurrence network. As can be seen from Fig. 5, the separated research topics include the information system and the 3D/nD modeling application which are the foundation for further BIM implementations. Sustainability related studies, including green building and energy simulation over the life cycle of buildings, are also part of the knowledge base. Other notable topics include interoperability, the integration of BIM and GIS, BIM performance assessment, the innovation on cost, schedule, safety, quality and risk management of BIM, ontology, as well as BIM communication and BIM education.

The knowledge domains are the structured subdivisions of BIM

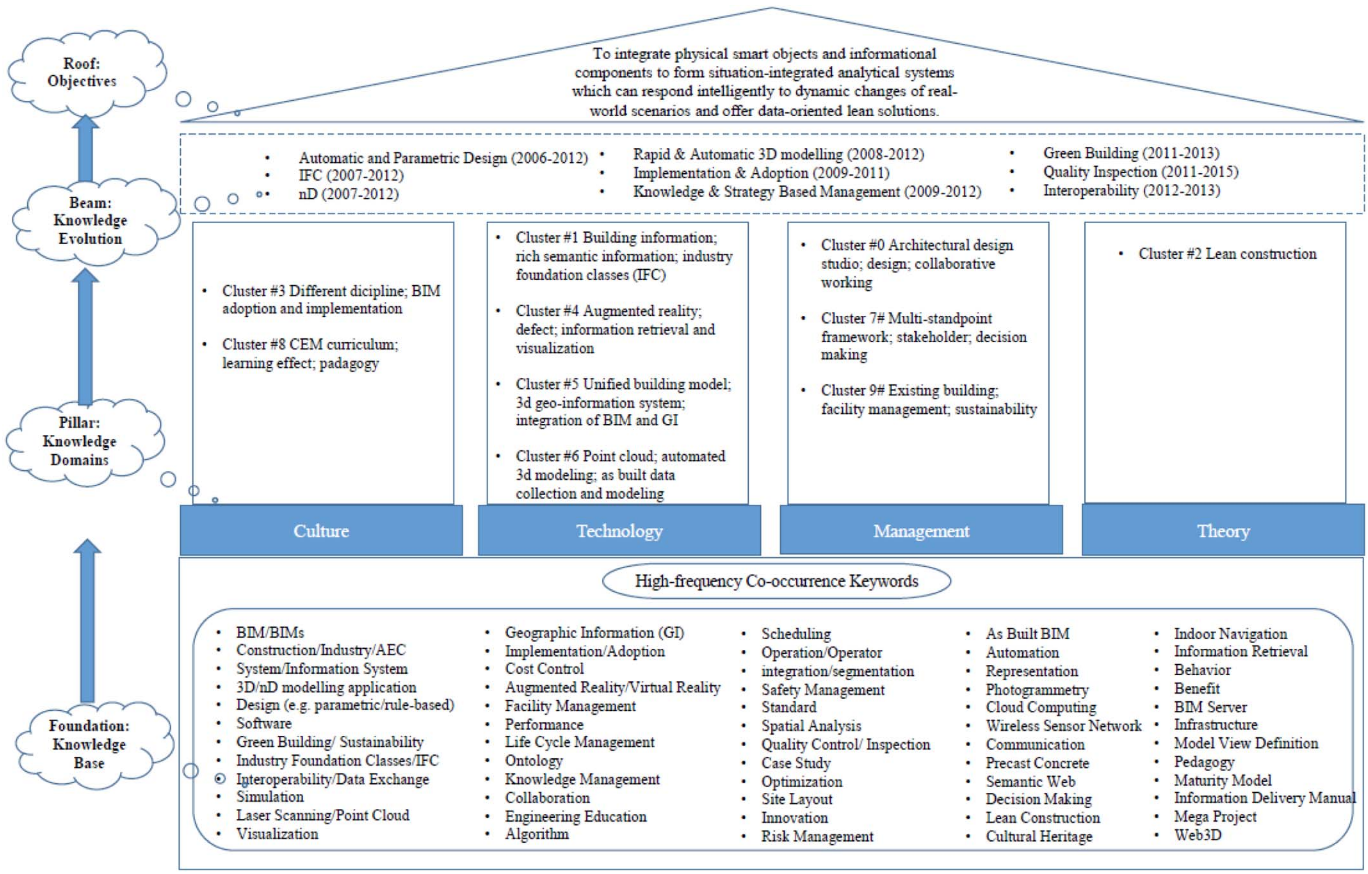


Fig. 5. The BIM knowledge map.

knowledge which can promote the understanding and implementation of BIM. Ten clusters, including architectural design studio, building information, lean construction, different discipline, augmented reality, unified building model, point cloud, multi-standpoint framework, CEM curriculum and existing building are identified. These clusters are further organized into four pillars, including culture, technology, management, and theory. The culture pillar focuses on multi-discipline in BIM and fostering a culture to improve the collaboration of different disciplines through industry adoption and acceptance models, education and pedagogy. In addition, the technology pillar focuses on developing BIM-integrated tools and systems which are necessary to improve productivity, reduce environmental impacts and increase profitability. It includes four clusters, namely point cloud (which addresses the automatic development of a three-dimensional BIM model), unified building model (which addresses the integration of 3D–GI and BIM for space and layout planning), building information (which aims to enable interoperability through innovations such as Web3D), as well as augmented reality (which addresses information visualization and retrieval issues in the real world, such as on a construction site).

The management pillar addresses the interaction between different stakeholders and how these stakeholders manage various aspects of BIM development and BIM implementation during the building life cycle. It has three clusters, namely the architectural design studio (e.g. design management for collaborative working), the existing building (e.g. facility management and sustainability), and the multi-standpoint framework (e.g. stakeholders and the decision-making process). One interesting finding is that the lean philosophy represents a significant pillar in the BIM knowledge map. The BIM platform provides accurate and dynamic planning and controlling which are extremely useful for lean implementations such as just-in-time and value stream mapping. In addition, as the lean philosophy has been heavily adopted in the manufacturing industry, many studies have been focused on the integration of lean and BIM in the prefabrication industry (see Fig. 5).

Over the past few years, an evolution pattern can also be identified for BIM to demonstrate the development process of both theoretical and empirical studies of BIM. As can be seen from Fig. 5, in the early years of BIM development, much attention has been focused on the automatic 3D design (2006–2012) and modeling (2008–2012), as well as the use of such 3D models for implementation and adoption (2009–2011) to address multi-dimensional issues (2007–2012). Along with the development, interoperability has been a critical issue. While previous studies focus on the International Foundation Classes (IFC) as the open standard model to allow interoperable applications (2007–2012), studies from 2012 to 2013 focus on addressing universal interoperability issues in the BIM platform (e.g. see [27,88]). It should also be noted that the use of BIM in green building and for quality inspection has attracted much attention in the periods of 2011–2013 and 2011–2015 respectively. From the analysis of knowledge base, domain and evolution in the BIM field, a clear BIM framework and development process of BIM knowledge can be identified. However, there still are numerous barriers related to human, software, machine, and environment factors. For example, one recent challenge is that dynamic changes (e.g. as-built information) cannot be accurately synchronized in a timely manner with BIM to support decision making [92]. It indicates that the interoperability, communication and situation awareness of software-to-machine and machine-to-machine should be enhanced in future works. In addition, big data assisted lean solutions have not been automatically generated and implemented by integrating the BIM with physical smart objects to control and plan the management process in the design, construction and maintenance stages of a facility [93]. Consequently, the ultimate goal of BIM proposed in this study is to integrate physical smart objects (clusters #0, #4 and #6) and informational components (cluster #1) to form situation-integrated analytical systems (clusters #4 and #5) which can respond intelligently to the dynamic changes (clusters #3, #7 and #9) of real-world scenarios and offer data-oriented lean solutions (cluster #2) [93]. The National Building Information Model Standard – United States (NBIMS-US Version 3) defines BIM as a digital representation of physical and functional characteristics and the use of shared knowledge resource to support life cycle decision making [94]. The BIM goal proposed in this study provides clarifications on the physical and functional characteristics, shared knowledge source and life cycle decision making.

The BIM knowledge map provided in Fig. 5 represents the status quo of the BIM knowledge. As BIM is a rapidly expanding field of study and highly multi-disciplinary, the knowledge base, domains and evolution pattern may change in the future. However, the mapping method and the knowledge map in this study represents a dynamic platform which can integrate future changes.

The review from the bibliometric approach can contribute significantly to the current manual review of BIM. The manual review focuses heavily on experts' opinion using a content analysis method. As such, a broader range of relevant topics may be overlooked by the experts who target specific sub-areas of BIM. For example, Ding et al. [60] classified 135 articles into a previously established classification and tended to provide a comprehensive BIM framework. This framework includes project management, stakeholders, and project life cycle. It should be noted that information (e.g. model view definition and information delivery manual) and policy (e.g. education) related studies, which are found to have high co-occurrences by the bibliometric approach, are overlooked in this framework. In addition to the advantage of comprehensiveness, the other distinct advantage of the bibliometric approach is that it can be conducted as frequently as needed to provide updated BIM knowledge. For example, Succar [15] offered a systematic investigation of relevant fields of BIM and categorized BIM knowledge from policy, process to technology fields. Based on the bibliometric review, many emerging research areas from 2009 have been identified and should be included in the BIM framework. Some of the typical examples are lean construction (cluster #2), augmented reality (cluster #4) and point cloud (cluster #6).

6. Conclusions

BIM knowledge is highly multi-disciplinary which includes the integration, storage, and exchange of data from several areas. Due to this ability to address multi-faceted problems, BIM has been recognized as one of the most appropriate platforms for the Architecture, Engineering and Construction industry, which is considered to be multi-organizational and multi-disciplinary.

This study refers to 1874 BIM-related articles. The analysis of these bibliographic records provides a unique and interesting snapshot of the BIM knowledge base, domains, and evolution. Specifically, the results show that a total of 60 key research topics are identified as the knowledge base of BIM. The most important ones include information system, 3D/nD modeling application, design, sustainability, IFCs and interoperability, BIM implementation, multi-dimensional (nD) BIM, real-time communication and BIM education. In addition, ten knowledge clusters are identified, including architectural design studio, building information, lean construction, different discipline, augmented reality, unified building model, point cloud, multi-standpoint framework, CEM curriculum, and existing building. These ten clusters are categorized into four pillars, including culture, technology, management and theory, which can be considered as the knowledge domains of BIM. In addition, the evolution of BIM knowledge has key milestones, including 3D design (2006–2012), modeling (2008–2012), the use of 3D models for implementation and adoption (2009–2011), nD BIM (2007–2012), IFCs (2007–2012), universal interoperability (2012 – 2013), green building (2011 – 2013) and quality inspection (2011–2015).

The contribution of this article to the body of knowledge is to quantitatively and accurately propose a BIM knowledge map based on the knowledge base, domains, and evolution by using bibliometric data. The methodology detailed in this article can be generalized and used as an effective tool for mapping discipline knowledge, compared to the more traditional literature reviews that are often adopted. It is recommended that future studies should be conducted periodically to further improve the BIM knowledge map provided in this study.

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