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Mapping the Knowledge Domain of Building Information Modelling (BIM): A Bibliometric Approach

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Abstract

Since 2002, building information modelling (BIM) has flourished expeditiously and has been adopted broadly in the field of built environment. In step with this explosive implementation and adoption, scores of articles have been published on BIM. Given this flood of documents over the last decade, the objective of this study to use a bibliometrics approach to help discover and benchmark the most valuable and highly cited publications in this burgeoning area. Not only do these techniques facilitate the identification of research clusters and topics in BIM community, but the approaches help highlight how research topics evolve over time, greatly contributing to understanding the underlying structure of the BIM knowledge base, domain, and evolution. Based on the knowledge base, knowledge domain and evolution of BIM knowledge, a BIM knowledge map is proposed. Although the depth and scope of this analysis are limited in some aspects, it 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.

Keywords: Building Information Modelling (BIM), Bibliometrics; Literature review; Knowledge map.

1. Introduction

The core functionality of Building Information Modelling (BIM) is to provide users the ability to integrate, analyze, simulate and visualize the geometric or non-geometric information of a facility. The concept was firstly raised by Eastman (1975). The terms: 'Building Information Model' and 'Building Information Modelling' (mean modeling building information, such as ontology development), were firstly used in publications of Van Nederveen and Tolman (1992) and Tolman (1999). However, much attention was only paid to BIM (meaning the process of generating and managing a facility with physical and functional information), when BIM was commercially promoted by Autodesk in 2002. Due to its potential 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 BIM 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 by scientific literature. By definition, the scientific literature is a group of publications centering on the practical or theoretical issues in various research areas (Chen et al., 2006). For example, Volk et al. (2014) find that the 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 the organization and legal issues. In order to uncover the hidden connections of scientific literature, many studies have been conducted to review the past development and propose new research trend of BIM (see Jung and Joo, 2011; Cerovsek, 2011; Tang et al. 2010). However, it should be noted that these reviews are typically qualitative, subjective and based on the manual review, which can be more biased and limited in terms of the number of articles that can be reviewed (Yalcinkaya and Singh, 2015).

In order to address the issues brought about by manual review, various bibliometrics approach (i.e. co-citation and co-occurrence analysis) assisted literature reviews have been developed and widely applied in informatics. However, these techniques are not frequently used in the construction sector. This is unfortunate, because understanding the hidden connections of various knowledge domains is significant to the development of research within that discipline to address gaps in the literature and to be distinct enough from existing work to make a viable contribution (Wei et al., 2015). As such, a few studies have been initiated to use these co-citation and visualization tools to map the underlying structures of BIM. For example, He et al. (2016) 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.

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 visualisation tools based on studies from 2004-2015; 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 domain 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.

2. Background

Knowledge development is a dynamic process that often leads to the arising of particular research fields. For example, in the field of BIM, many sub-areas have formed in the past few years, ranging from policy to process and technology (Succar, 2009). In the BIM field, since its inception in 1975, most scholars incline to concentrate on one or two specific themes under a BIM sub-area that finally contribute to the whole body of knowledge. For example, there are studies focusing on the themes under BIM-related policy area, such as the BIM standards (Cheng and Lu, 2015), implementation strategies (Howard and Björk, 2008), organization (Dossick and Neff, 2009), intellectual property (Fan, 2013) and education (Becerik-Gerber et al., 2012). The knowledge development is always accompanied by the specialization, which unavoidable causes knowledge fragmentation. For example, in the area of BIM-related processes, there are overmuch fragmented topics which focus on cost management (Lee et al., 2014), procurement (Grilo and Jardim-Goncalves, 2011), quality (Park et al., 2013), scheduling (Kim et al., 2013), energy (Larsen et al., 2011), change (Francom and El Asmar, 2015), design (Azhar et al., 2011), safety (Zhang and Hu, 2011; Feng et al., 2015), space (Isikdag et al., 2008), workflow (Sacks et al., 2009), risk (Chien et al., 2014), model (Tang et al., 2010), facility (Kang and Hong, 2015), supply chain (Irizarry et al., 2013), investment (Giel and Issa, 2011) and stakeholders (Succar, 2009). The unexpected result is that many dynamics connections between specific themes are unheeded, disregarded, or both. As BIM is considered as an information technology enabled platform which can integrate inter-disciplinary collaboration, the major knowledge bursts in BIM could be followed by the technology development on information retrieval (Yeh et al., 2012), visualization (Yan et al., 2011), exchange (Jeong et al., 2009), interaction (Yan et al., 2011), modelling (Xiong et al., 2013) and interoperability (Grilo and Jardim-Goncalves, 2010). It should be noted that although some studies are the fundamental building blocks of the BIM knowledge, others may be simply practical applications or implementations of the BIM technology, which add limited value to the growth of the BIM knowledge.

In order to identify the fundamental building blocks of the BIM knowledge and their connections, there are many reviews which have been conducted. However, the collection of the BIM knowledge in literature is massive, 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 manual review and may have a high level of bias. For example, Wong and Zhou (2015) reviews the use of BIM in enhancing sustainability and found that the current fundamental blocks of green BIM are the implementations in the design and construction stages. Similarly, Bradley et al. (2016) use a critical review to investigate the use of BIM for infrastructure and finds that ICT system development and the modeling of infrastructure projects are the fundamental pillars in the research area. Tang et al. (2010) conducted reviews to survey the adoption of laser-scanned point clouds for BIMs creation and found that filling the gaps among existing promising techniques and algorithms could become a foundamental burst for automated as-built BIM creation. Despite the importance of identifying fundamental building blocks of the BIM knowledge, few studies have been conducted on BIM in a broader context.

The Scientific literature contains both persistent and transient elements (Price, 1976). 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 (Kleinberg, 2003). 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 (Chen et al., 2010). Meanwhile, a systematic exploration of the knowledge domains in BIM will benefit the establishment of a scientific theory in BIM by identifying the key foundations that the BIM knowledge stands on.

3. Research method

In this study, two datasets of bibliographic records on ‘Building Information Modelling (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 as the core dataset. The expanded dataset represents a broader context of the core. Key findings, including the identification of the knowledge domain 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. The strategy is also adopted by many previous studies, such as Chen et al. (2012) and Chen et al. (2014).

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 a 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^{TM} 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 Modelling. 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, review and proceedings papers from 2004 to 2015.

3.1.3 The expanded dataset

The expanded dataset includes extra r ecords 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 is originated from the principle of citation index by Garfield and Sher (1963). In the citation report of WoS, the core dataset is cited by 938 records. These records are merged into the core dataset to get the expanded dataset which consists of 1874 records. The bibliometrics approach adopted in this study is based on both datasets shown in Table 1.

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

3.2 Data analysis

3.2.1 Bibliographic map of BIM

The bibliographic map of the BIM can be represented by a network of a variety of 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 keywords co-occurrence network and document co-citation network. And these two techniques have a few obvious advantages over the conventional manual review mthod. First, the more extensive and more diverse range of the related topics can be investigated than the manual review. Second, such techniques can be applied to generate the reviews as frequently as needed, although an individual does not have ample capacity to conduct critical manual review in a specific field.

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 “hotspots” (e.g., research focuses or research topics) in a time period (Su and Lee, 2010). 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 (Chen et al., 2010). If two documents are frequently jointly cited, then 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 (Chen et al., 2010). 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 on 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 the BIM knowledge.

4. Results

4.1 The knowledge domain in the core dataset

4.1.1 Document Co-citation Analysis

Figure 1 shows the overview of the document co-citation network generated from the core dataset with 230 nodes and 701 links, and it is visualized and analyzed by the Citespace. As can be seen from Figure 1, Citespace divides the timeline (2004-2015) into a series of time slices (each time slice equals to one year). The top-cited publications (top,

50 publications) during each time slice are selected for subsequent analysis. Nodes represent cited the reference in the core dataset, and the links connecting nodes represent co-citation relationships. To facilitate easy interpretation, link colors correspond directly to each time slice. 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 the BIM knowledge.

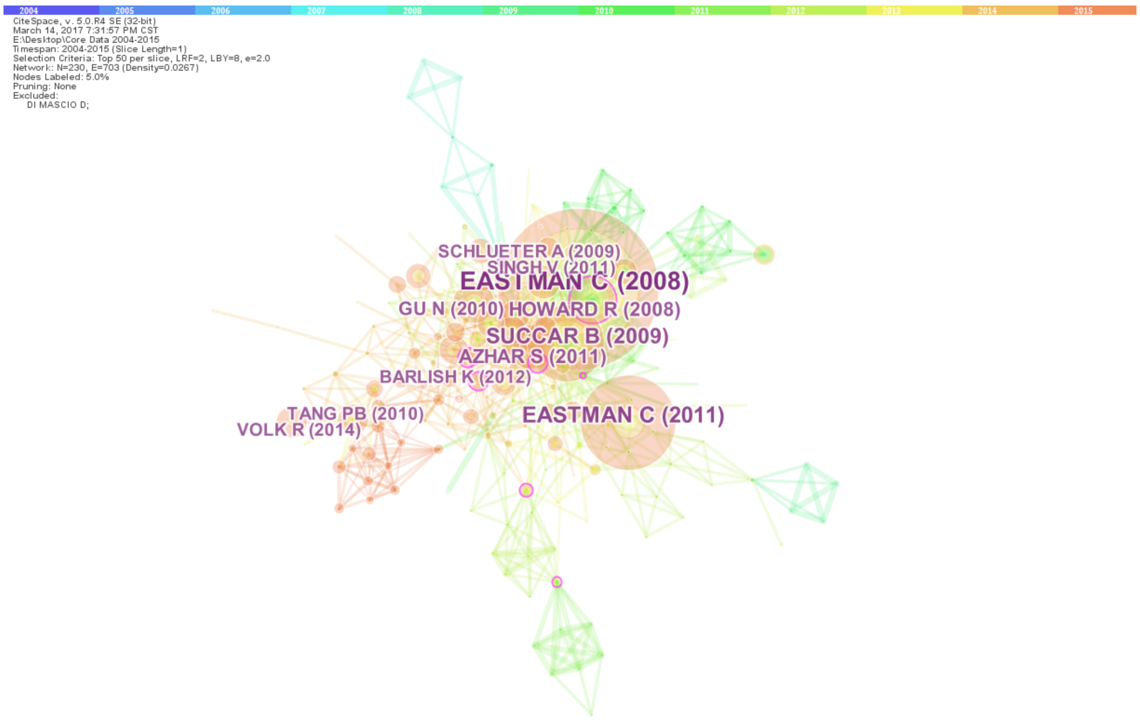

Figure 1. Document co-citation network of BIM studies

Based on Figure 1, the top ten cited publications from 2004 to 2015, including two editions of the book and four journal articles, are shown in Table 2. The first two are two editions of BIM Handbook (Eastman et al., 2011) which serve as an introduction of BIM for professionals and researchers within varied disciplines. These two editions of BIM Handbook are essential resources in the BIM discipline. Although the majority of documents citing these two editions of handbook are journal articles, which is contrary to the citation habits of many disciplines (Najman and Hewitt, 2003), this is not uncommon for BIM because these two editions of handbook contain fundamental conceptual and methodological knowledge that is discipline agnostic (e.g., can be easily borrowed and implemented by other fields). The other eight journal papers are review-oriented, focusing on particular BIM implementation and adoption in AEC industry. For example, Succar (2009) explores some of the publicly available international guidelines and introduces the BIM framework, which is a research and delivery foundation for industry stakeholders. Howard and Björk (2008) conducts a qualitative study based on information from a number of international experts and has asked a series of questions about the feasibility of BIMs (refer to the files which can be retrieved, extracted, exchanged or networked to support decision-making regarding a facility), the conditions for the BIM success, and the role of standards with particular reference to the International Foundation Classes (IFC).

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.	2008	145	Book
Eastman, CM., Teicholz, P., Sacks, R., & Liston, K.	A guide to building information modeling for owners, managers, designers, engineers and contractors.	2011	87	Book
Succar, B.	Building information modelling framework: A research and delivery foundation for industry stakeholders.	2009	72	Automation in construction
Howard, R., & Björk, B. C.	Building information modelling–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

In sum, regardless of the subarea, all ten publications represent BIM as a key technology for pursuing substantive research issues in the life cycle of a facility from physical or social aspects. It is interesting to observe that the cited frequency generated by Citespace is somewhat different from the results on Google Scholar or WoS. For example, Gu (2009) has been cited more than 327 times on Google Scholar and more than 90 times on WoS but cited frequency produced by Citespace present only 37 citations. Although this might seem like an alarming inconformity between the exact citation times and the number of times extracted by Citespace, citation count of all publications are reduced in this way. Recall that 938 collected publications employed in this analysis are retrieved by a phrase “Building Information Model*” and a word “BIM” during a confined time period (2004-2015) . Accordingly, Citespace gives a narrow subtotal of all citations for a specific topic, rather than an exhaustive, summary number of citation times for all topics within and outside of the BIM. Further, the three major citation databases of WoS available from Thomson Reuters do not include all BIM-related Journals (e.g. Journal of Information Technology in Construction) or Proceedings, nor are all years for certain publications indexed. Therefore, although subtotal cited frequency corresponding to BIM looks small for each of the key nodes in this analysis, there is no systemic bias and the results demonstrated by Citespace are both representative and meaningful.

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 delimiting 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 noun phrases of each cluster and noun phrases are extracted from titles, keywords and abstracts of citing publications. Top-ranked terms became candidate cluster labels. Three specialized metrics including log-likelihood ratio (LLR) test (Dunning 1993), term frequency-inverse document frequency (TF∗IDF) (Salton et al., 1975) and mutual information (MI) tests are used for this process. LLR test is a statistical tests to compare two model's goodness of fit on the basis of likelihood ratio. In citespace, it provides the best results in terms of the uniqueness and coverage (Chen et al., 2010). Figure 2 shows the labeled clusters with abstract terms and their relative importance via LLR test (with the largest cluster numbered as #0 and the smallest cluster numbered as #9). Additional metrics, such as TF∗IDF (it is a numerical metric to reflect how important a word is to a corpus) and MI tests (it signifies a reduction in uncertainty measures of how much one random variable tells us about another), are also applied to represent the most salient aspect of the clusters (Chen et al., 2010). All three are authentic techniques for identifying cluster themes..

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From an explanatory perspective, the size of a cluster is decided by the total number of publications that a cluster includes. Table 3, exported from Citespace, specifies the largest 10 clusters in rank order. The values of the silhouettes for each cluster are greater than 0.65, suggesting robust and meaningful results.

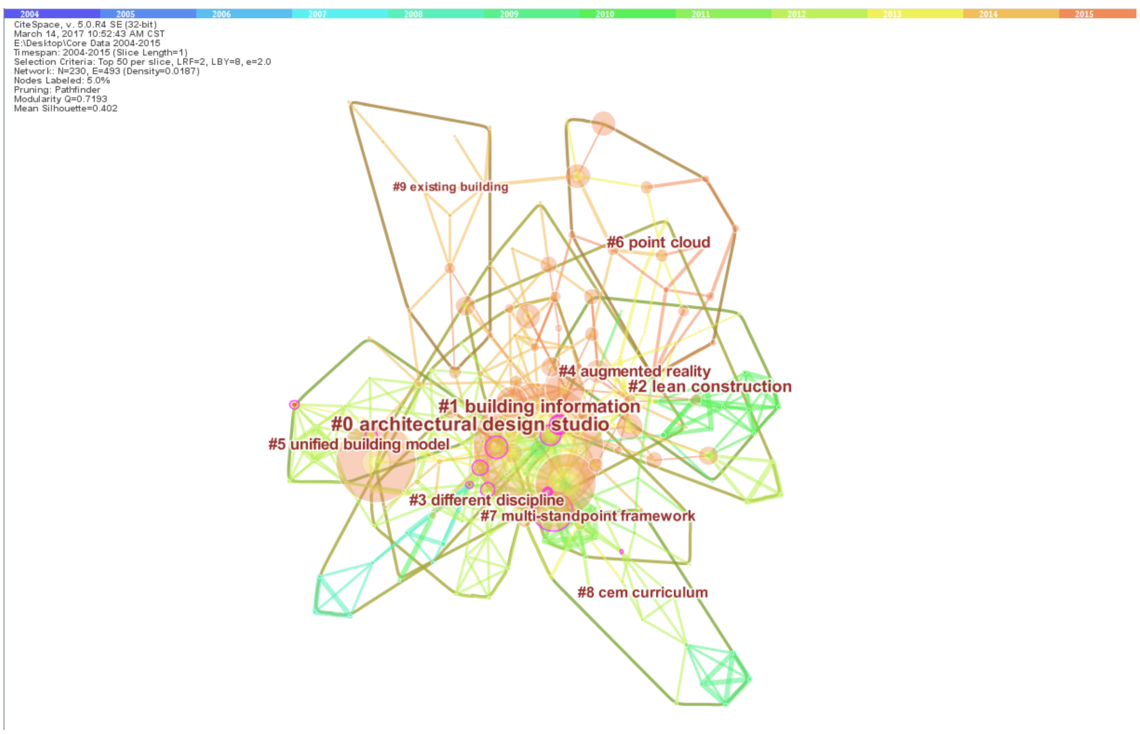

Figure 2. Clusters of knowledge domains within the BIM discipline

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	industrialized construction	2007

				management system		
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	padagogy	2008
9	11	0.78	existing building (2232.36, 1.0E-4)	facility management	sustainability	2009

Interestingly, the clusters for building information, augmented reality, architectural design studio and different discipline are almost adjacent to each other within the network and are linked by various nodes (e.g. publications). This indicates that documents published by authors in these four clusters were cited by scores of the same publications and compelling overlap exists within this knowledge domain. An alternative presentation for visualizing these clusters and their network is via timeline view (See Figure 3). This technique provides a temporal overview of nodes, links, and clusters. The most apparent finding in Figure 3 is that most of the documents cited were published after 2002, roughly coincide with the wide availability and adoption of BIM related software (e.g. Autodesk Revit).

Within the architectural design studio cluster, which includes 27 articles, there are citations to the Lee et al. (2006), Azhar et al. (2011), Singh et al. (2011) and Zhang et al. (2013), etc. These studies related to architectural design studio disclose the most concerned issue regarding the facility design, covering parametric design, sustainable design, design for the safety and constructability , and collaborative working. In fact, “ design” and “collaborative working” are the key terms for this cluster if the TF*IDF and MI clustering algorithms are used. These links within the BIM knowledge domain make intuitive sense. Researchers are interested in optimizing the design process and outputs, along with parametric design, sustainable design, design for safety and constructability, is especially concerned with improving collaborative working among different disciplines by using BIM. Not surprisingly, this cluster covers the BIM studies in the early stage of the life-cycle building, reflecting the importance of design stage in BIM knowledge domain.

The second most significant cluster relates to building information. The studies included in this cluster build a major foundation of the knowledge domain regarding the information exchange among heterogeneous BIM tools, applications, and systems (Fu et al., 2006; Taylor and Bernstein, 2009; Jeong et al., 2009; Grilo and Jardim-Goncalves, 2010; Venugopal et al., 2012). The standardized and re-usable model view definitions (MVDs) were recognized as recommended method to support industry foundation classes (IFC) data schema for improving the information interoperability, particularly semantics information. It is worth mentioning that the building information cluster is paid constant attention by researchers, with most of the citing articles published between 2004 and 2015. As detailed previously, this indicates a core part of BIM knowledge domain.

Another main cluster pertains to lean construction. Again, this concentrates on substantive issues regarding helping smooth the construction and information flow, thereby minimizing variation, the waste of material, time and human resources, and improving coordination and construction quality. In mots instances, these studies include lean principles (e.g. constraints management, pull method, Just-in-time) involvement, work process simulation, and workspace analysis (et al., 2009; Sacks et al., 2010; Sacks et al., 2010). In all instances, BIM plays a significant role in both managing the information and visualizing the work process for lean construction. Corresponds to this stream of studies, the industrialized construction including prefabricated construction, modular construction, precast construction, also leverages BIM and lean construction for enhancing construction planning and control. In fact, lean construction originated from the Toyota Production System (TPS) which is a production planning and control approach. So the production based characteristics of industrialized construction make it an essential role in lean construction.

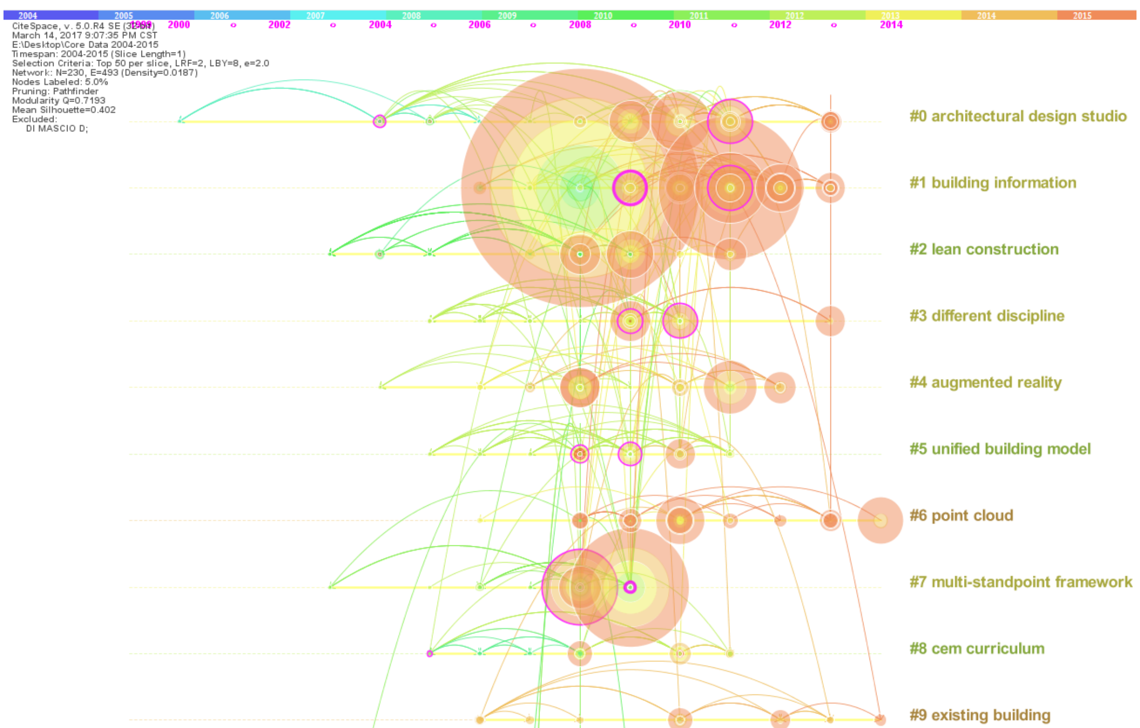

Figure 3. Timeline view for BIM knowledge domains: 2004-2015

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4.1.3 Keyword Co-occurrence Network (Knowledge base)

Since keywords provide information about the key content of publications, an analysis of keywords can help identify research topics in BIM-related studies. After standardizing for similar words or different words with the similar meaning (for example, “BIM”, “building information modeling”, “building information modelling”, or “building information models”, “BIM technology” are mapped to “BIM/BIMs”). Figure 4 shows the overview of the keyword co-occurrence network generated from the core dataset with 485 nodes and 1588 links. A node represents one author keyword. The size of each node is proportional to the co-occurrence frequencies of the related keywords. Table 4 lists the top 60 terms with the total 2442 co-occurrence frequencies, which account for more than 90% among all the keywords frequencies.

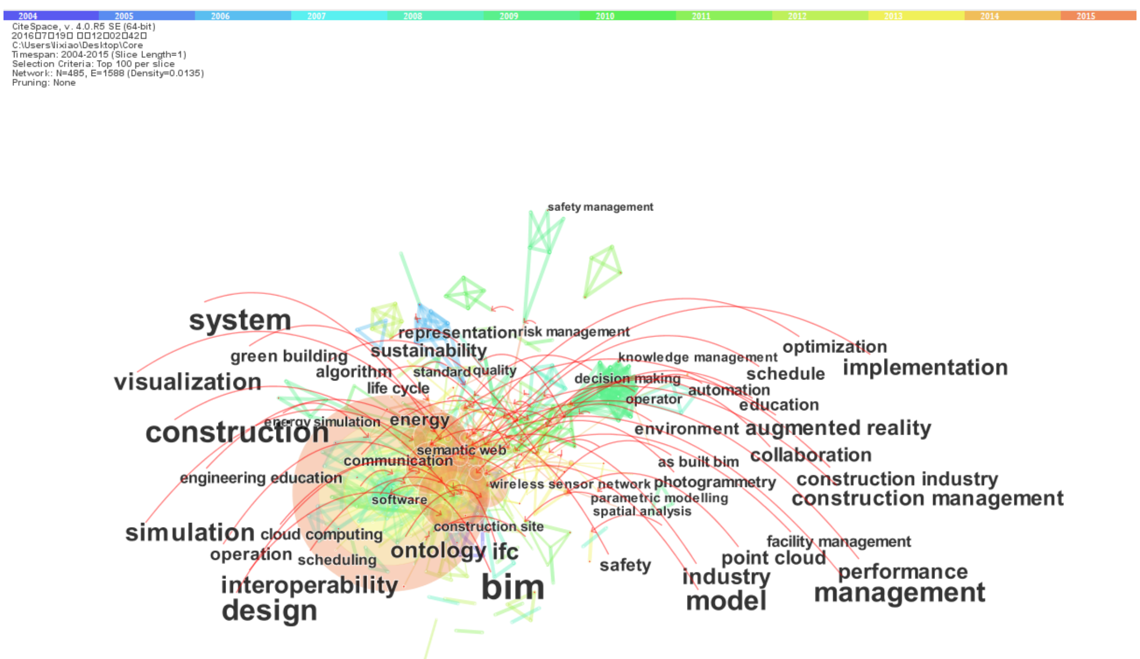


Figure 4. Keywords Co-occurrence network

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 Modelling 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

As can be seen from Figure 4 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 modelling application are the second largest hotspots in BIM research, appearing 148 and 112 times respectively. Therefore, it can be reasonably concluded that the information system and 3D/nD modelling application are the basic components in BIM research. The term "Design" is the third largest hotspot with 100 occurrences. BIM is firstly 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 active 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 (Azhar et al., 2011; Basbagill et al., 2013). Most green BIM research centers on the environmental performance of the development (Wong et al., 2013) , design (Azhar et al., 2011) and construction (Bynum et al., 2012) stages of building lifecycles. 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 (Costa et al., 2013), retrofitting (Motawa and Almarshad, 2013), and demolition stages (Cheng and Ma, 2013).

Industry foundation classes and interoperability is a critical topic for using BIM as a robust system in the life cycle of various projects. Because knowledge sharing frameworks between different stakeholders in a building project have relatively high priority, IFC provides a rich schema for interoperability through object-based transactions in 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 (Venugopal et al., 2015).

The BIM domain and the Geographic Information System (GIS) domain shares 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. (2008) investigate 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. (2013) establish a prototype system to integrate BIM and GIS to enable tracking 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 (Kang and Hong, 2015).

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 (Abdirad, 2016). 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. (2016) proposed a structural equation model (SEM) 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 (Succar and Kassem, 2015).

The innovation on cost, schedule, safety, quality and risk management in BIM also form an important domain. This also facilitates the development of multi-dimensional (nD) modeling in BIM. The nD model provides a database allowing all stakeholders to retrieve necessary information through the same system, which allows them to work cohesively and efficiently during the whole project life-cycle (Ding et al., 2014). The database can be used to address various project requirements, including scheduling (Kim et al., 2013), costing (Lee et al., 2014), stability (Sacks et al., 2010), sustainability (Schlueter and Thesseling, 2009), maintainability (Motawa and Almarshad, 2013), evacuation simulation (Rüppel and Schatz, 2011) and safety (Zhang et al., 2013), each of which can be considered as one additional dimension to the traditional 3D BIM model.

The effectiveness of real-time communication within BIM environment is somehow restrained due to the nature of BIM which can be examined as virtual objects (Jiao et al., 2013). An emerging topic in BIM is to combine virtual reality and augmented reality with BIM to address low productivity in retrieving information, the tendency of committing an error in assembly, and low efficiency of defect inspection (Wang et al., 2014). Virtual reality based simulator (either non-immersive or immersive) have been developed to provide construction managers with opportunity of experiencing challenges of real-life projects through simulated scenarios (Goulding et al., 2014)

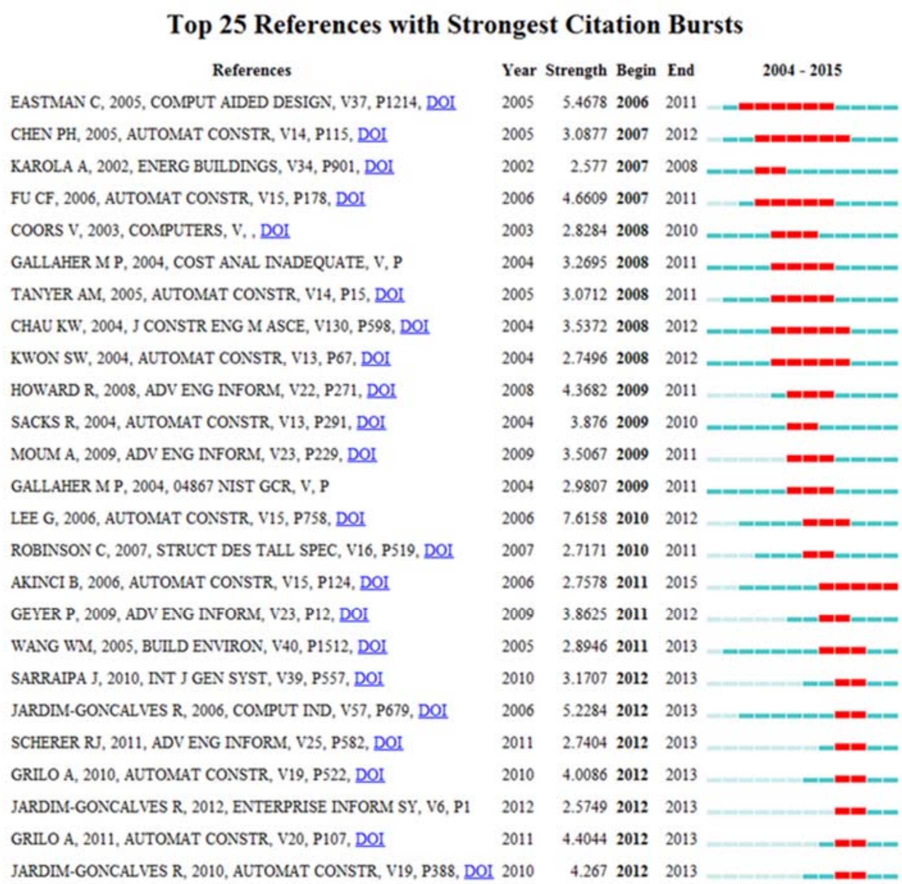
BIM education, which may include the integration of BIM into mainstream civil engineering and construction management courses, also has a relatively high frequency. Using BIM technology as an integrated format in construction education will be able to provide students with a higher quality training on the skills and knowledge required by the industry. A rich and collaborative learning environment will be achieved through purposeful attempts of integrating BIM into various course contents (Becerik-Gerber et al., 2012).

Although there are numerous other clusters and keywords identified from Table 2 and Table 3 could be detailed, the primary aim of this analysis should be clear. The ten largest clusters and their relevant keyword co-occurrences extracted by CiteSpace represent most, if not all, of the principal 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 Figure 2 , Figure 3 and Figure 4, it is accessible to notice that BIM is an interdisciplinary domain and comprehend the adoption and influence of BIM on numerous research areas.

4.2 The evolution of BIM knowledge in the expanded dataset

The expanded dataset, consisting of 1,874 records (which is about twice as many as the core dataset), puts the core dataset in a broader context with contributions from a total of 4,126 distinct authors from 2,360 institutions. These additional records are included because they cited 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.

Citation burst can be used an indicator to understand the knowledge trend during a specific period of time. Figure 5 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. (2005), 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. This burst ended in 2011. Sacks et al. (2004) also have a citation burst 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. It also concludes that 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.



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

Figure 5. Top 25 references with strong citation bursts

The bursts starting from 2007 are mainly focusing on industry foundation classes. Chen et al. (2005) present 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. (2006) present the details of the development of an IFC viewer, which is designed to be an integrated interface for nD modeling applications. Karola et al. (2002) have 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 (2008), Chau et al. (2004) and a report by Gallaher et al. (2004). The strongest burst in 2008 by Howard and Björk (2008) 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. (2004) and Tanyer and Aouad (2005) lead to a new trend of research on 4D simulation and planning. The former paper presents a 4D visualization model that aims to help construction managers plan day-to-day activities more efficiently and also help practical site management activities by understanding the relevance of modern computer graphics to site management activities. The latter one develops 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, Gallaber et al. (2004) identifies and estimates 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. (2004) and Coors (2003). These two studies investigate 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 visualizing respectively which are often cited by subsequent research.

Citation bursts starting during 2009 to 2011 are led by Lee et al. (2006), Geyer (2009) and Moum et al. (2009). Among them, Lee et al. (2006) have the strongest citation burst in the entire expanded dataset. It explored the extent to which design and engineering knowledge can be practically embedded in production software for building information modeling (BIM) and focuses 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 (2009) applies 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. (2009) and Robinson (2007) 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. Figure 5 shows that the areas of design (Geyer, 2009) and green building (Wang et al., 2005) and quality (Akinci et al., 2006) have strong bursts. Wang et al. (2005) present 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 solution(s) for a predefined problem. Akinci et al. (2006) outline 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 the interoperability. For example, the strongest citation in interoperability happens to Grilo and Jardim-Goncalves (2011), who discusses the potential value of interoperability and strategies to enhance interoperability between computer systems and applications. Jardim-Goncalves and Grilo (2010) proposes 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 (Jardim-Goncalves and Grilo, 2010). 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 (Sarraipa et al., 2010). However, in spite of 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 (Scherer and Schapke, 2011).

5. Discussion and Implication

The need for a systematic and comprehensive BIM knowledge map and framework has been highlighted by many studies. For example, Succar (2009) argues 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 (2009), BIM knowledge is organized into three fields, including policy, process, and technology. He et al. (2016) summaries the managerial areas of BIM knowledge and finds that there are five principal research areas, including stakeholder, adoption process, conceptual framework, application approach and working environment. The major uniqueness of this study are to use a systematic and quantitative bibliometrics approach for clearly visualizing and interpreting the knowledge base, knowledge domain and knowledge evolution of BIM. The findings of hidden connections among knowledge base, domain and evolution could be integrated to form the BIM knowledge, which is shown in Figure 6.

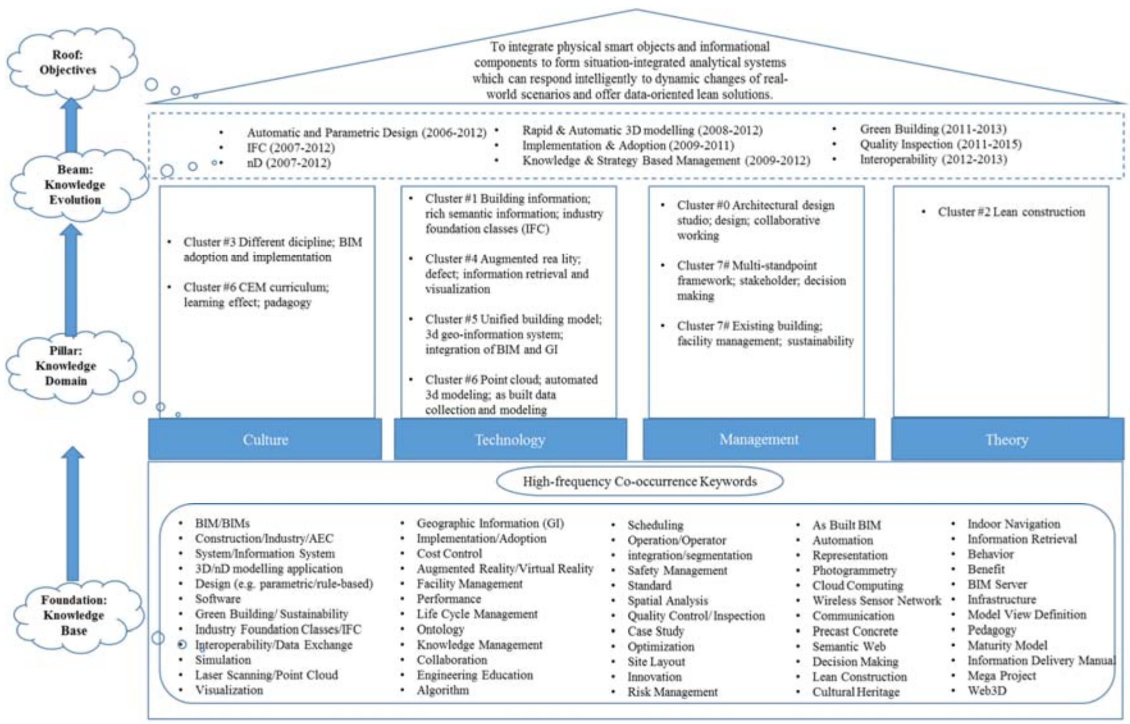


Figure 6. The BIM Knowledge Map

Figure 6 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 Figure 6, the separated research topics include the information system and the 3D/nD modelling 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, as well as BIM communication and BIM education.

The knowledge domains are the structured subdivisions of BIM knowledge which can promote understanding and eventually promote the 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, existing building. 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 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 real world, such as on 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 architectural design studio (e.g. design management for collaborative working), existing building (e.g. facility management and sustainability), and multi-standpoint framework (e.g. stakeholders and 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 Figure 6).

It should be noted that the ultimate goal of BIM is to integrate physical smart objects and informational components to form situation-integrated analytical systems which can respond intelligently to dynamic changes of real-world scenarios and offer data-oriented lean solutions (Anumba, 2015). Go further, the current BIM development has come to a bottleneck which the dynamic changes (e.g. as-built information) could not be real-time synchronizing with BIM to truly support decision making and big data assisted lean solutions have not been automatically generated and implemented by integrating the BIM with physical smart objects to control and planning the design, construction and maintenance stage of a facility. Over the past few years, an evolution pattern can also be identified for BIM to reach the ultimate goal. As can be seen from Figure 6, 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 a 2012-2013 focus on addressing universal interoperability issue in the BIM platform (e.g. see Grilo and Jardim-Goncalves, 2010; Grilo and Jardim-Goncalves, 2011). It should also be noted that the use of BIM in green building and for quality inspection have attracted much attention in the periods of 2011-2013 and 2011-2015 respectively.

The BIM knowledge map provided in Figure 6 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.

6. Conclusions

The BIM knowledge is highly multi-disciplinary which includes the integration, storage, and exchange of data from multiple disciplines. Due to its benefit when addressing multi-disciplinary problems, BIM has been highly 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 implies that a clear understanding of the BIM knowledge, especially its knowledge base, knowledge domains and knowledge evolution, is imperative.

This study has drawn findings from 1,874 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, 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 the BIM knowledge has key milestones, including 3D design (2006-2012), modelling (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 knowledge base, domains and evolution by using bibliometric data. The methodology detailed in this article is highly generalizable and can be 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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