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Review

# A scientometric review of global BIM research: Analysis and visualization

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ABSTRACT

In the recent years, building information modeling (BIM) has transformed the architecture, engineering, and construction industry, and attracted attentions from both researchers and practitioners. However, few studies have attempted to map the global research on BIM. This study conducts a scientometric review of global BIM research in 2005–2016, through co-author analysis, co-word analysis and co-citation analysis. A total of 614 bibliographic records from the Web of Science core collection database were analyzed. The results indicated that Charles M. Eastman received the most co-citations and that the most significant development in BIM research occurred primarily in the USA, South Korea and China. Additionally, BIM research has primarily focused on the subject categories of engineering, civil engineering and construction & building technology, and the keywords "visualization" and "industry foundation classes (IFC)" received citation bursts in the recent years. Furthermore, 10 co-citation clusters were identified, and the hot topics of BIM research were: mobile and cloud computing, laser scan, augmented reality, ontology, safety rule and code checking, semantic web technology, and automated generation. This study provides researchers and practitioners with an in-depth understanding of the status quo and trend of the BIM research in the world.

## 1. Introduction

Building information modeling (BIM), defined as shared digital representation of physical and functional characteristics of any built object that forms a reliable basis for decisions [1], has been transforming the architecture, engineering, and construction (AEC) industry in many countries [2]. From the mid-2000s, AEC industry practitioners started to adopt BIM in projects. To enhance BIM adoption, various researches on BIM have been conducted in the last decade. Some researchers focus on the technical issues relating to BIM, while others deal with the non-technical issues. Obviously, BIM is not just a technology, but also a project management tool and process [3], which consists of all aspects, disciplines, and systems of a facility within a model and enables all project participants (owners, architects, engineers, contractors, subcontractors and suppliers) to collaborate more accurately and efficiently than traditional processes [4]. Thus, several benefits brought by BIM have been reported, such as significant project cost and time savings [5], reduced errors and omissions, reduced rework, maintained repeat business [6], and enhanced construction productivity [7].

In the last decade, BIM research has been diverse and more emerging technologies have been integrated into BIM. For example, BIM is capable of facilitating 3D printing implementation [8] and has been used in the 3D printing of small-scale models and large-scale buildings, respectively [9]. Mahdjoubi et al. [10] developed a model to help deliver real-estate services by integrating 3D laser scanning and BIM. Wang et al. [11] proposed a conceptual framework that integrates BIM with augmented reality (AR) in order to enable the real-time visualization of the physical context of each construction activity or task.

Previous researches also include reviews of BIM research. For example, Tang et al. [12] surveyed the techniques that can be utilized to automate the process of reconstructing as-built building information models from laser-scanned point clouds; Cerovsek [13] provided a review of the standards for data exchange and features of over 150 AEC/O (Architecture, Engineering, Construction, and Operation) tools and digital models, and proposed a framework for enhancing both BIM tools and schemata; and Volk et al. [14] presented a review of BIM implementation and research in existing buildings, and identified challenges that hindered BIM implementation. However, limited efforts have been made to outline and visualize the research trends of BIM research.

Scientometrics is defined as the "quantitative study of science, communication in science, and science policy" [15, pp.75], and includes the measurement of impact, reference sets of articles to investigate the impact of journals and institutes, understanding of scientific citations, mapping scientific fields and the production of indicators for use in policy and management contexts [16]. This study

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attempts to conduct a scientometric review of the scientific literature relating to BIM and gain a snapshot of this research field in 2005–2016. The findings can provide researchers with a better understanding of the current state of the BIM research in the world and identify the hot topics in the literature. All of the bibliographic records used in this study have been published by the Web of Science (WOS) core collection database.

## 2. Method

This study analyzed all the articles in the WOS core collection database, which consists of the most important and influential journals in the world [17,18], and includes most publications on BIM. After pre-analysis and comparison, the following retrieval code is used in the WOS core collection: *TS* = (*building information model* AND BIM**). Here, "*" denotes a fuzzy search and "TS" means an article subject. In this study, only journal articles were selected for analysis, while book reviews, editorials, and conference papers were excluded. This is because journal articles usually provide more comprehensive and higher-quality information than other types of publications, and most reviews in the area of construction management have only covered journal articles [19–21]. Additionally, the research areas obviously irrelevant to BIM (e.g., biology, medicine, agriculture, etc.) were excluded as well. Finally, a total of 614 bibliographic records were collected in early January 2017. The first journal article on BIM [22] was published in 2005. Thus, the time span of these records was 2005–2016. Fig. 1 shows the distribution of the 614 bibliographic records in 2005–2016. The total number of records significantly increased in 2012–2015, but dropped slightly in 2016.

The software package CiteSpace can visualize and analyze literature of a scientific knowledge domain, which is broadly defined to capture the notion of a logically and cohesively organized body of knowledge [23]. Domain analysis has been recognized as an advantageous scientometric approach to discovering the implications hidden in a vast amount of information and tracing development frontiers [18,24]. CiteSpace is strong in mapping knowledge domains through systematically creating various accessible graphs [23]. Therefore, CiteSpace 5.0 was used to analyze the literature of BIM.

Three types of bibliometric techniques were applied in this study: (i) co-author analysis that seeks author co-occurrences, country co-occurrences, and institution co-occurrences; (ii) co-word analysis that processes keywords or terms to analyze word co-occurrences; and (iii) co-citation analysis that identifies co-cited authors, co-cited articles, and co-cited journals. These techniques have been recommended by previous studies of a similar nature [18,25]. In addition, cluster analysis was performed based on the co-citation analysis results, and citation bursts showing a surge of citations of publications were detected. In CiteSpace, the burst detection is based on the algorithm developed by Kleinberg [26].

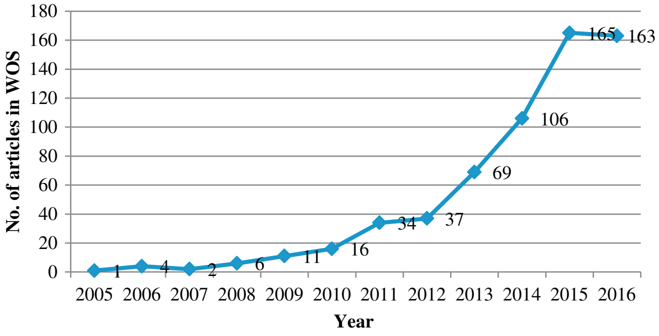

**Fig. 1.** The number of articles on BIM in the WOS core collection in 2005–2016.

**Table 1**
The top 10 most productive authors.

| Author | Institution | Country | Count | Percentage |
|---|---|---|---|---|
| Rafael Sacks | Technion - Israel Institute of Technology | Israel | 20 | 3.3% |
| Xiangyu Wang | Curtin University | Australia | 16 | 2.6% |
| Charles M. Eastman | Georgia Institute of Technology | USA | 14 | 2.3% |
| Ghang Lee | Yonsei University | South Korea | 11 | 1.8% |
| Burcu Akinci | Carnegie Mellon University | USA | 10 | 1.6% |
| Raja R A Issa | University of Florida | USA | 10 | 1.6% |
| Hyoungkwan Kim | Yonsei University | South Korea | 10 | 1.6% |
| Jochen Teizer | RAPIDS Construction Safety and Technology Laboratory | Germany | 10 | 1.6% |
| Jun Wang | Curtin University | Australia | 10 | 1.6% |
| Peter E D Love | Curtin University | Australia | 9 | 1.5% |

## 3. Results and discussions

### 3.1. Co-author analysis

The information of the article authors is available from the bibliographic records, which enables the identification of the leading researchers, institutions and countries for BIM research. Thus, a co-authorship network and a network of co-authors' institutions and countries/regions were generated.

### 3.1.1. Co-authorship network

According to the number of journal publications, the top 10 most productive authors were identified. As shown in Table 1, Rafael Sacks (Technion-Israel Institute of Technology), Xiangyu Wang (Curtin University) and Charles M. Eastman (Georgia Institute of Technology) occupied the top three positions.

A co-authorship network is shown in Fig. 2, where each node represents an author and the links between the authors denote the collaboration established through the co-authorship in the articles. The network pruning was used to remove excessive links through Pathfinder, which is recommended by Chen and Morris [27]. Finally, there were 146 nodes and 173 links in the co-authorship network. The node size represents the number of publications, and the thickness of the links indicates the levels of the cooperative relationships in a given year. The colors of links, e.g., blue, green, yellow, orange and red, correspond to different years from 2005 to 2016, as shown in Fig. 3.

In terms of the collaboration, there are several closed-loop circuits in Fig. 2, indicating that the researchers in these circuits have established strong collaboration, such as the circuit of Rafael Sacks, Charles M. Eastman, and Yeon-Suk Jeong. In addition, several research communities were identified, where many authors worked with one or two highly productive author. For example, Xiangyu Wang and Jun Wang were the two central authors of a research community, including Martijn Truijens, Yi Jiao, Shih-Chung Kang, etc.; and Inhan Kim was the central author of a research community, consisting of Zhenhua Shen, Karam Kim, Jungho Yu, etc. In graph theory, Freeman's betweenness centrality is defined as the ratio of the shortest path between two nodes to the sum of all such shortest paths [28]. A node with a high betweenness centrality usually connects two or more large groups of nodes with the node itself in-between, and can be detected by a purple ring in CiteSpace. With such nodes, clusters in a network can be separated [29] and revolutionary scientific publications can be identified [30]. In Fig. 2, Charles M. Eastman (centrality = 0.13), Jun Wang (centrality = 0.11), Jochen Teizer (centrality = 0.11) and Yong-Cheol Lee (centrality = 0.1) are nodes with purple rings, and they connect different groups of authors.

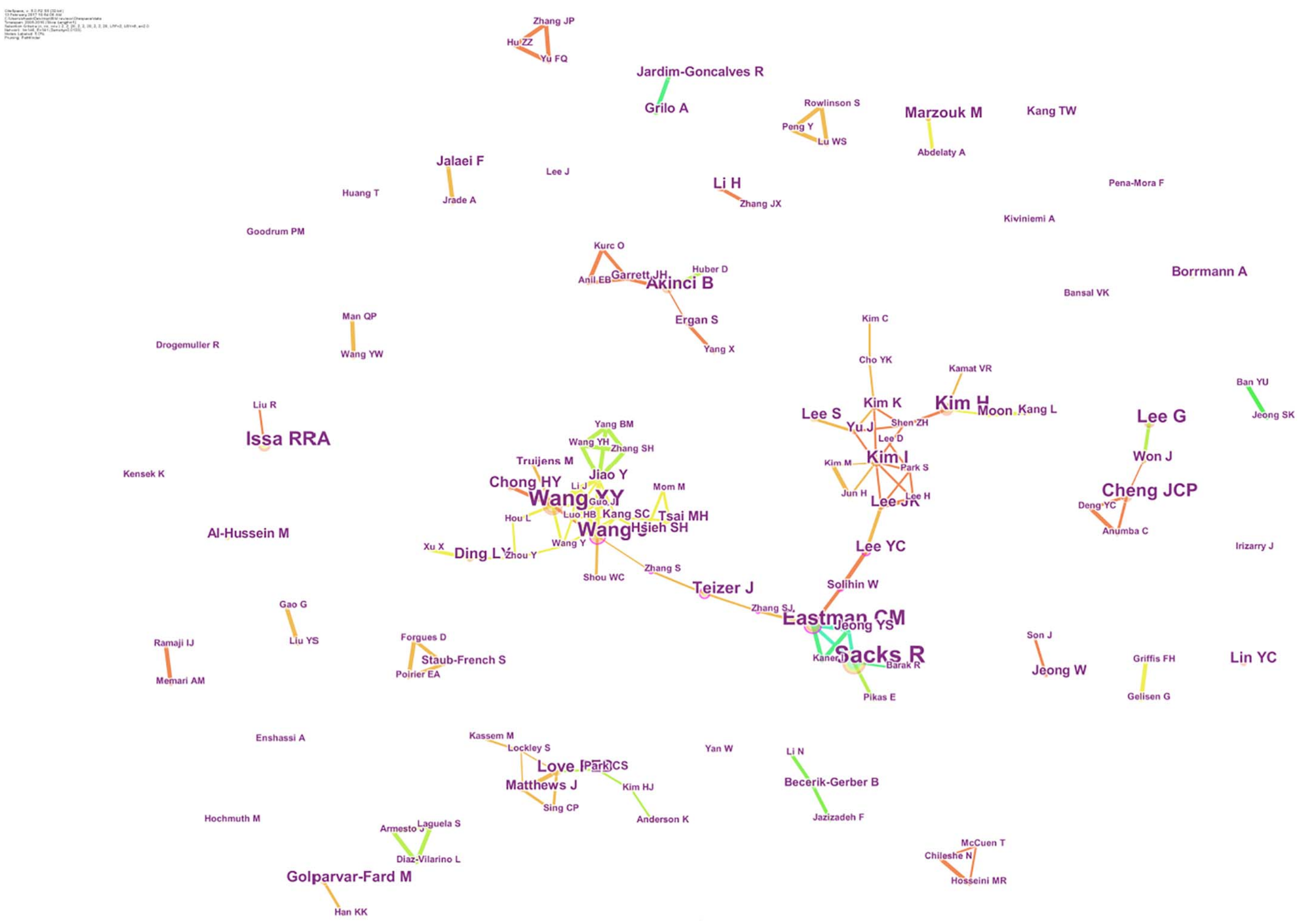

**Fig. 2.** Co-authorship network.

#### 3.1.2. Network of countries/regions and institutions

A network was produced based on the contributions of institutions and countries/regions to explore the distribution of articles on BIM. This research power network includes 135 nodes and 377 links. The node size denotes the total number of articles published in 2005–2016. As shown in Fig. 4, the USA (196 articles), South Korea (95 articles), China (71 articles), Australia (63 articles) and England (54 articles) has made major contributions to the articles on BIM. The large number of journal publications in these countries/regions implied that BIM research had been advanced in these countries. It was not surprising that the USA had made the greatest contribution to BIM because this technology originated from the USA and many American companies have developed commercial BIM software packages. In addition, regarding international collaborations, researchers from the USA have widely collaborated with those from other countries, such as Canada, Australia, South Korea, Spain, Turkey, and Germany.

The contributions of institutions were also identified. The BIM research progress has been very active at institutions, such as Georgia Institute of Technology (36 articles), Curtin University (26 articles), Kyung Hee University (23 articles), Technion-Israel Institute of Technology (20 articles), and Hanyang University (16 articles). These institutions can be seen as the publication centers for BIM research around the world.

Additionally, the nodes with high betweenness centrality were identified and highlighted by purple rings in Fig. 4. Countries/regions such as South Korea (centrality = 0.75), China (centrality = 0.51), the USA (centrality = 0.45), England (centrality = 0.43), and Canada (centrality = 0.26) and institutions such as Georgia Institute of Technology (centrality = 1.03), Curtin University (centrality = 0.75), Hanyang University (centrality = 0.67), Kyung Hee University (centrality = 0.63), and Chung Ang University (centrality = 0.61) have occupied key positions in the network and connected research activities between different countries/regions.

Furthermore, citation bursts representing notable increases in citation over a short period were found in countries/regions such as the USA (burst strength = 5.42, 2005–2012), England (burst strength = 3.34, 2007–2011), Israel (burst strength = 5.55, 2009–2010), and Portugal (burst strength = 3.40, 2010–2013), and at institutions such as Georgia Institute of Technology (burst strength = 4.10, 2005–2010), Technion-Israel Institute of Technology (burst strength = 5.71, 2009–2010), and University of Salford (burst strength = 3.10, 2010–2011). These suggested that the articles from these countries and institutions attracted an extraordinary degree of attention in the corresponding years. It is also worth attention that there have been no citation bursts in the past three years (2013–2016), which is consistent with the fact that BIM research has attracted worldwide attention in the recent years. Thus, a single country/region or institution may find it difficult to receive high citations over a short

**Fig. 3.** Link colors corresponding to years 2005–2016.

**Fig. 4.** Network of countries/regions and institutions.

period.

### 3.2. Co-word analysis

In the recent years, there have been various topics and themes in BIM research. Co-word analysis can help estimate trends and frontiers of BIM research.

#### 3.2.1. Network of co-occurring subject categories

In the WOS core collection database, each journal publication was assigned with one or more subject categories according to the corresponding journal. A network of the co-occurring subject categories in BIM research, including 38 nodes and 112 links, was produced to analyze the emerging trends, as shown in Fig. 5. The node size denotes the number of articles within each category. Engineering (463 articles), civil engineering (368 articles), construction & building technology (257 articles), computer science (123 articles) and multidisciplinary engineering (70 articles) were found to have the most abundant publication records.

It is worth reiteration that the colors of links, e.g., blue, green, yellow, orange and red, correspond to different years from 2005 to 2016 (see Fig. 2). In the past four years, there have been an increasing number of articles in the subject categories of environmental engineering, environmental sciences & ecology, business & economics, management, green & sustainable science & technology, robotics, etc. This suggested that the potential of BIM in energy and environmental analysis, sustainable design, and life cycle assessment (LCA) had been recognized and attracted great attention from academia [31–33]. The building and construction industry has greatly contributed to the global climate change [34,35], and thus experienced a shift towards green buildings and sustainable construction [36,37]. In addition, BIM technologies have been adopted to address management issues. For example, Lin [38] attempted to enhance interface management by using three-dimensional interface maps integrated into BIM; and Wetzel and Thabet [39] developed a BIM-based framework to support safe maintenance and repair practices during the facility management phase. Furthermore, robotics with 3D cameras have been used to facilitate the generation of as-built building information models [40].

Several nodes received high betweenness centrality, as indicated by purple rings, such as the categories of construction & building technology (centrality = 0.69), thermodynamics (centrality = 0.53), energy & fuels (centrality = 0.48), green & sustainable science & technology (centrality = 0.46), computer science (centrality = 0.46), multidisciplinary engineering (centrality = 0.39), and environmental sciences (centrality = 0.25). They represented the turning points connecting the research in different phases and significantly influenced the development of BIM research. In addition, citation bursts were found in two subject categories: architecture (burst strength = 4.42, 2009–2012) and computer science-software engineering (burst strength = 2.57, 2011–2012), suggesting that the publications in these two categories were the most active areas in the development of BIM research.

#### 3.2.2. Network of co-occurring keywords

Keywords present the core contents of articles and show the

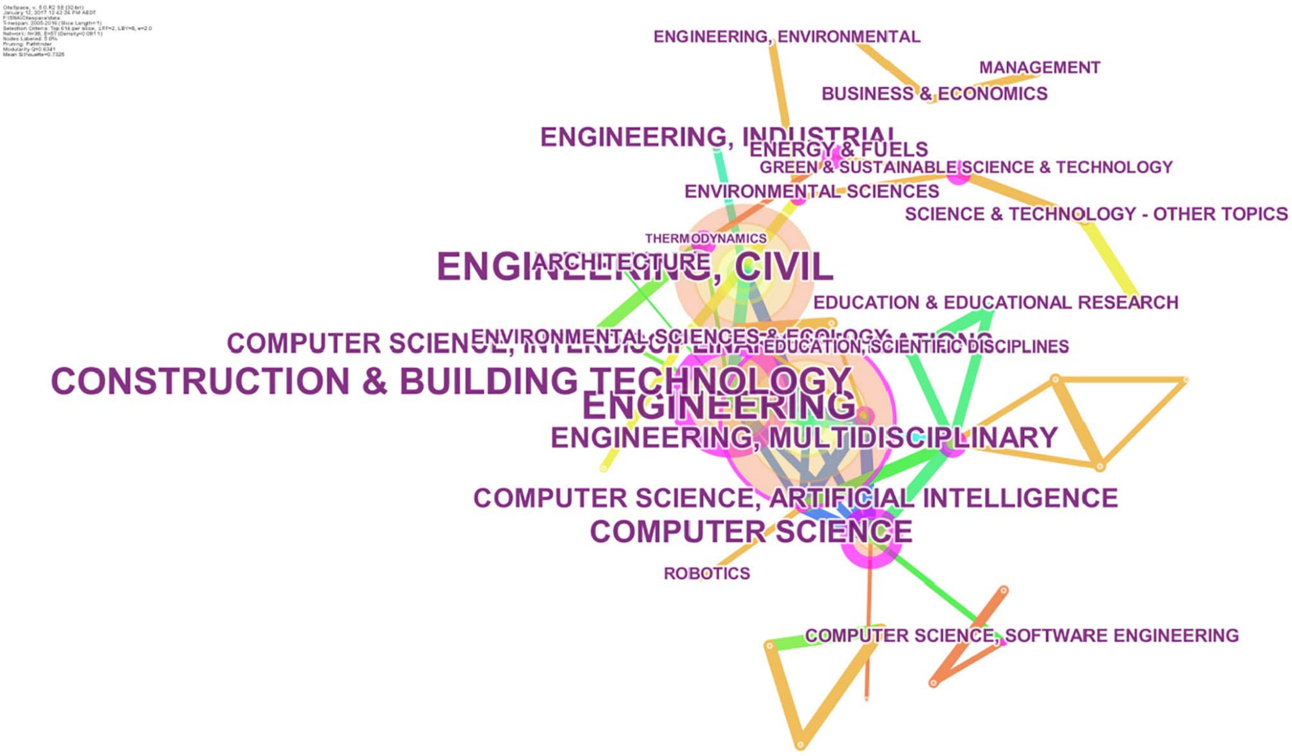

**Fig. 5.** Network of co-occurring WOS subject categories.

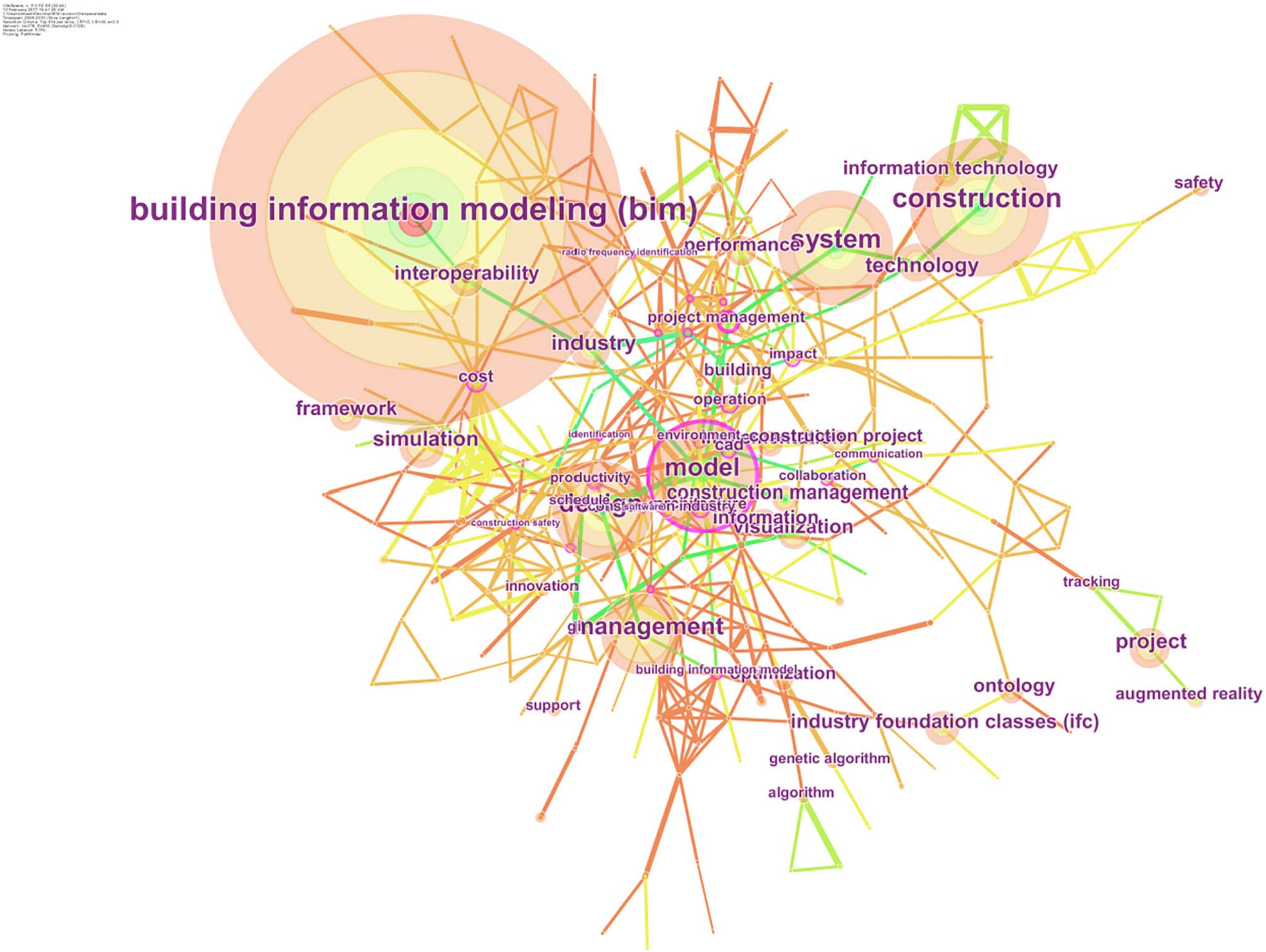

**Fig. 6.** Network of co-occurring keywords.

development of research topics over time. In the WOS database, there are two types of keywords: (i) "author keywords", which are supplied by authors, and (ii) "keywords plus", which are identified by the journals. Both types of keywords from the 614 bibliographic records were used to construct a network of co-occurring keywords. Citespace allows users to merge the nodes that are in fact the variants of the same entity. Thus, similar keywords, such as "building information modelling", "building information modeling" and "BIM", were merged into "building information modeling (BIM)". Fig. 6 shows the network of co-occurring keywords, with 278 nodes and 770 links

The node size represents the frequency with which a keyword occurred in the dataset. The top 10 high-frequency keywords were "building information modeling (BIM)" (frequency = 329), "system" (frequency = 95), "model" (frequency = 86), "design" (frequency = 84), "management" (frequency = 69), "simulation" (frequency = 40), "project" (frequency = 36), "industry" (frequency = 34), and "technology" (frequency = 34). In addition, some keywords received relatively high betweenness centrality scores, such as "model" (centrality = 0.23), "schedule" (centrality = 0.23), "project management" (centrality = 0.22), "productivity" (centrality = 0.21), "architecture" (centrality = 0.18), and "impact" (centrality = 0.18). They connected different research topics and significantly influenced the development of BIM research. In addition, six keywords were found to be citation bursts: "building information modeling (BIM)" (burst strength = 6.67, 2009–2012), "CAD" (burst strength = 2.65, 2010–2011), "interoperability" (burst strength = 3.03, 2010–2012), "three-dimensional model" (burst strength = 2.61, 2010–2013), "visualization" (burst strength = 3.08, 2011–2012), and "industry foundation classes (IFC)" (burst strength = 2.85, 2012–2013), indicating that these were the hot topics in BIM research in the corresponding years

### 3.3. *Co-citation analysis*

Co-citation can be defined as the frequency with which two documents are cited together by other documents [41] and has been recognized as a proximity measure for documents. In this study, co-citation analysis consists of journal co-citation analysis, author co-citation analysis and document co-citation analysis.

Cluster analysis was used to detect and analyze the emergence of and abrupt changes in research trends over time and to identify the focus of a research trend at a particular time in the context of its intellectual basis. Clusters were arranged to reveal the significant intellectual turning points driving research trends and the interconnections between different research trends.

**Table 2**
The top 10 source journals for BIM research in 2005–2016.

| Source journal | Host country | Count | Percentage |
|---|---|---|---|
| Automation in Construction | Netherlands | 160 | 26.06% |
| Advanced Engineering Informatics | UK | 41 | 6.68% |
| Journal of Computing in Civil Engineering | USA | 40 | 6.51% |
| Journal of Construction Engineering and Management | USA | 31 | 5.05% |
| Journal of Information Technology in Construction | Sweden | 27 | 4.40% |
| Journal of Management in Engineering | USA | 17 | 2.77% |
| Journal of Civil Engineering and Management | Lithuania | 12 | 1.95% |
| Energy and Buildings | Netherlands | 11 | 1.79% |
| Journal of Asian Architecture and Building Engineering | Japan | 11 | 1.79% |
| Journal of Professional Issues in Engineering Education and Practice | USA | 11 | 1.79% |

#### 3.3.1. *Journal co-citation network*

As shown in Table 2, the top 10 source journals for BIM research were identified, according to the statistics from the WOS core collection database. Automation in Construction had published 160 articles (26.06%) on BIM research and occupied the top position, followed by Advanced Engineering Informatics (41 articles) and the Journal of Computing in Civil Engineering (40 articles). Out of the 10 journals, four journals are published in the USA.

The references cited by the 614 retrieved records were analyzed, and then a journal co-citation network with 204 nodes and 657 links was produced to detect the most significant cited journals, as indicated in Fig. 7. The node size denotes the co-citation frequency of each source journal. With respect to co-citation frequency, the top five most influential journals were Automation in Construction (frequency = 451), the Journal of Construction Engineering and Management (frequency = 253), the Journal of Computing in Civil Engineering (frequency = 218), Advanced Engineering Informatics (frequency = 213), and the Journal of Information Technology in Construction (frequency = 97). It is worth noting that these five journals were also among the top source journals, in which articles on BIM were published. Thus, the journals with more contributions to BIM research also attracted more citations.

In Fig. 7, it is obviously that some nodes have high betweenness centrality and are highlighted by purple rings, such as the Journal of Computing in Civil Engineering (centrality = 0.66), the International Journal of Project Management (centrality = 0.52), the Journal of Construction Engineering and Management (centrality = 0.50), MIS Quarterly (centrality = 0.49), and Automation in Construction (centrality = 0.47). These journals represented major intellectual turning points and linked journals in different phases. Additionally, citation bursts were found at Automation in Construction (burst strength = 14.60, 2007–2012), the Journal of Computing in Civil Engineering (burst strength = 7.08, 2009–2012), the Journal of Information Technology in Construction (burst strength = 6.41, 2010–2012), the Journal of Construction Engineering and Management (burst strength = 6.04, 2009–2012), Computer Aided Design (burst strength = 5.76, 2005–2013), and Advanced Engineering Informatics (burst strength = 5.57, 2011–2012). These findings implied that the articles published in these journals received strong citations over a short period and were therefore worth following.

#### 3.3.2. *Author co-citation network*

Author co-citation analysis can identify the relationships among authors, whose publications are cited in the same articles and analyze the evolution of research communities. Fig. 8 presents the author co-citation network, containing 284 nodes and 980 links. The node size reflects the number of co-citations of each author, and the links between authors represent indirect cooperative relationships established based on co-citation frequency. Thus, the most highly cited authors were identified, including Charles M. Eastman (frequency = 325, USA), Salman Azhar (frequency = 89, USA), Rafael Sacks (frequency = 88, Israel), Burcin Becerik-Gerber (frequency = 72, USA), Bilal Succar (frequency = 58, Australia), Ghang Lee (frequency = 56, South Korea), Timo Hartmann (frequency = 47, Germany), Ning Gu (frequency = 43, Australia), Yusuf Arayici (frequency = 38, Turkey), Heng Li (frequency = 36, Hong Kong), and Umit Isikdag (frequency = 36, Turkey). The diversity in the location of these most highly cited authors demonstrated that BIM research had been widely performed around the world.

Authors with high betweenness centrality can be identified by the nodes with purple rings. Based on the betweenness centrality metric, Jennifer Whyte (centrality = 0.53), Richard Davies (centrality = 0.52), Changfeng Fu (centrality = 0.49), Kristen Barlish (centrality = 0.38), Bilal Succar (centrality = 0.34), and Jürgen Melzner (centrality = 0.30) occupied the top six positions, and they were major intellectual drivers of BIM research and connected research in different

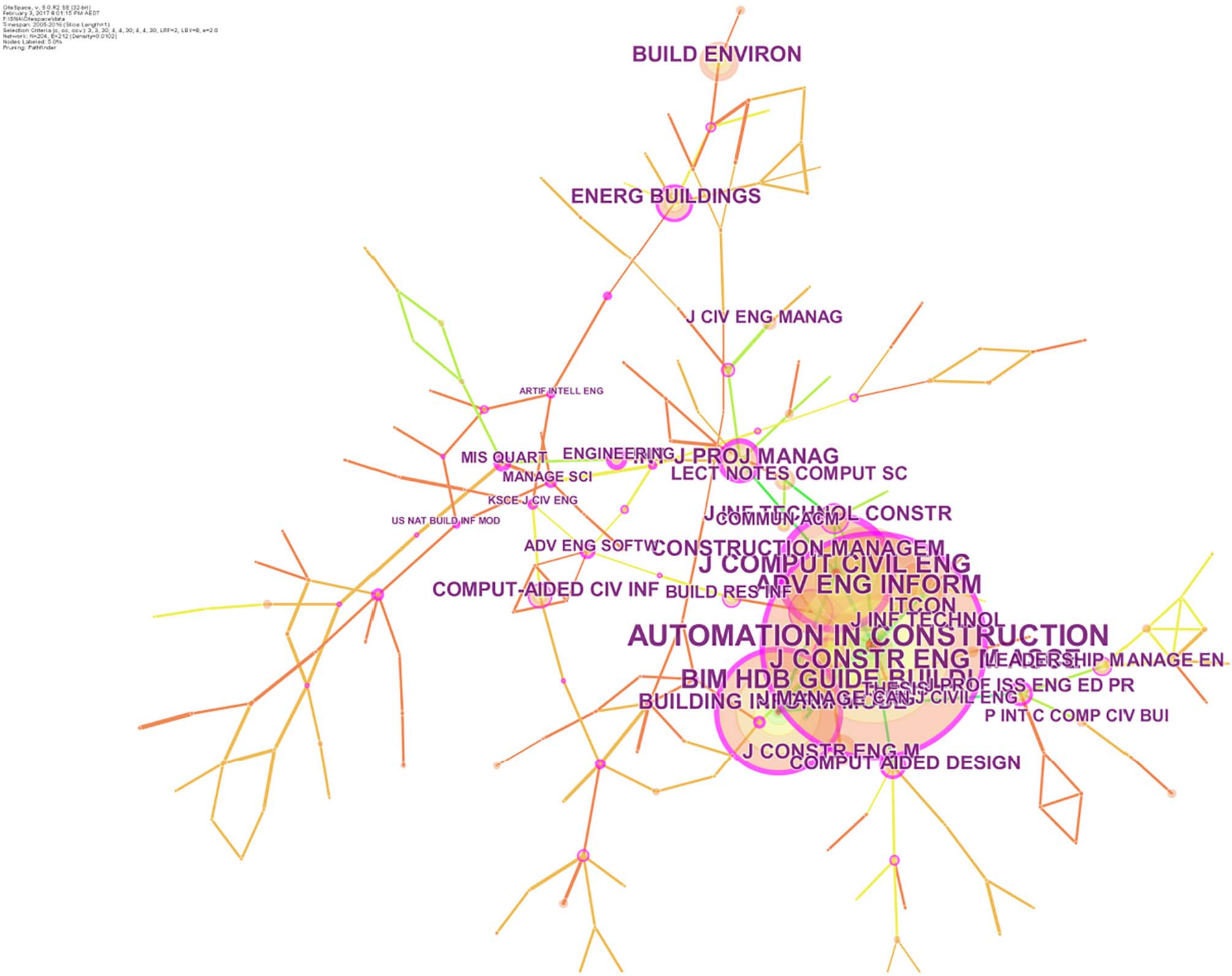

**Fig. 7.** Journal co-citation network.

research communities. A highly cited author does not necessarily receive a high betweenness centrality. However, when an author simultaneously receives a high citation count and a high betweenness centrality, this author is very likely to have a fundamental influence on the development and evolution of BIM research.

Furthermore, several authors had citation bursts, with rapid increases in citation frequency over short periods, including Charles M. Eastman (burst strength = 15.34, 2005–2012), Rafael Sacks (burst strength = 10.49, 2007–2012), Lachmi Khemlani (burst strength = 8.60, 2011–2013), Rob Howard (burst strength = 6.10, 2011–2014), Bilal Succar (burst strength = 4.87, 2012–2013), Godfried Augenbroe (burst strength = 3.20, 2012–2014), Ghang Lee (burst strength = 3.67, 2012–2013), Carrie S. Dossick (burst strength = 3.28, 2013–2014), Tomo Cerovsek (burst strength = 3.12, 2013–2014), John E. Taylor (burst strength = 2.98, 2013–2014), and Timo Hartmann (burst strength = 2.81, 2011–2014). They tended to affect the direction of BIM research and their articles were worth following. Although Bilal Succar was not among the most productive authors, he received a high co-citation frequency, high betweenness centrality and was among the citation bursts. According to the WOS database, his article [3] had received a total of 141 citations till the end of 2016.

### 3.3.3. Document co-citation network

Document co-citation analysis can analyze the underlying intellectual structures of a knowledge domain and demonstrate the quantity and authority of references cited by publications. In this process, co-citation clusters were identified. According to the WOS citation metric, the top 25 cited documents are summarized in Table 3. According to the WOS citation metric, Succar [3], Howard and Björk [42] and Gu and London [43] received 141, 88 and 84 citations, respectively, and occupied the top three positions. Succar [3] developed a BIM framework with defined knowledge components, setting a research and delivery foundation for industry stakeholders. Howard and Björk [42] collected a series of experts' views on BIM standards and proposed a framework that can help identify where particular BIM standards and solutions should be adopted in building projects. Gu and London [43] investigated the readiness of the industry with respect to the product, processes and people, to implement BIM, and highlighted the consideration into both technical and non-technical issues.

A network of document co-citations and co-citation clusters, which contains 147 nodes and 441 links, is presented in Fig. 9. Each node represents a document and is labeled with the first author's name and the publication year. Each link denotes the co-citation relationship between the two corresponding documents. The node size represents the co-citation frequency of the node document. It should be noted that the node documents were among the 16,129 documents cited in the 614 retrieved records, and were not necessarily included in the 614 retrieved articles. Eastman et al. [31] and Eastman et al. [44] received 107 and 77 co-citations, respectively, and thus occupied the top two positions, followed by Succar [3] (frequency = 53), Azhar [2] (frequency = 41), and Gu and London [43] (frequency = 36).

Documents with high betweenness centralities, as indicated by purple rings in Fig. 9, are also worth attention. The representative

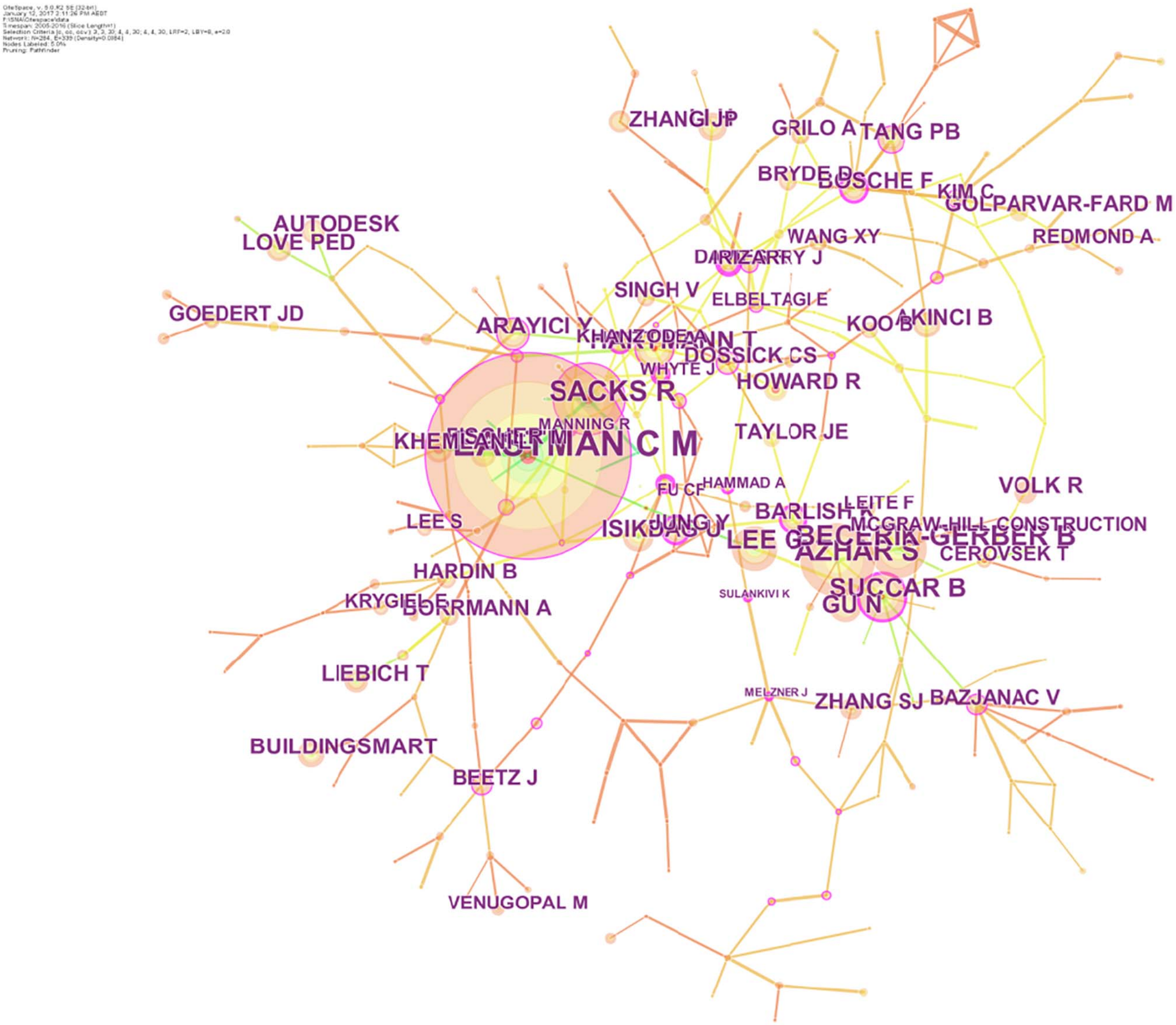

**Fig. 8.** Author co-citation network.

**Table 3**

The top 25 cited articles and an article with high betweenness centrality.

| No. | Total citations | Cluster ID | Betweenness centrality | Article | No. | Total citations | Cluster ID | Betweenness centrality | Article |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 141 | #0 | 0.23 | Succar [3] | 14 | 47 | #2 | 0.06 | Goedert and Meadati [59] |
| 2 | 88 | #0 | 0 | Howard and Björk [42] | 15 | 45 | #2 | 0.13 | Dossick and Neff [60] |
| 3 | 84 | #0 | 0.28 | Gu and London [43] | 16 | 40 | NA | NA | Geyer [61] |
| 4 | 74 | #9 | 0 | Zhang et al. [62] | 17 | 40 | #0 | 0 | Becerik-Gerber et al. [63] |
| 5 | 73 | NA | NA | Lee et al. [64] | 18 | 40 | #5 | 0.12 | Taylor and Bernstein [65] |
| 6 | 71 | #3 | 0.3 | Xiong et al. [57] | 19 | 39 | #3 | 0.01 | Brilakis et al. [66] |
| 7 | 70 | #2 | 0 | Singh et al. [55] | 20 | 39 | #1 | 0 | Zhang and Hu [67] |
| 8 | 58 | #0 | 0.03 | Azhar et al. [36] | 21 | 38 | #5 | 0.01 | Hartmann et al. [68] |
| 9 | 58 | #7 | 0.05 | Grilo and Jardim-Goncalves [69] | 22[a] | 37 | #6 | 0.37 | Irizarry et al. [47] |
| 10[a] | 57 | #5 | 0.43 | Jung and Joo [46] | 23[a] | 36 | #6 | 0.31 | Sacks et al. [49] |
| 11 | 56 | #0 | 0.09 | Bryde et al. [5] | 24 | 36 | #4 | 0.12 | Jeong et al. [70] |
| 12 | 54 | #5 | 0.05 | Barlish and Sullivan [71] | 25[a] | 36 | #7 | 0.33 | Sacks et al. [48] |
| 13 | 52 | NA | NA | Basbagill et al. [72] | [a] | 31 | #6 | 0.67 | Park et al. [45] |

NA = not applicable.

[a] Represents an article with high betweenness centrality.

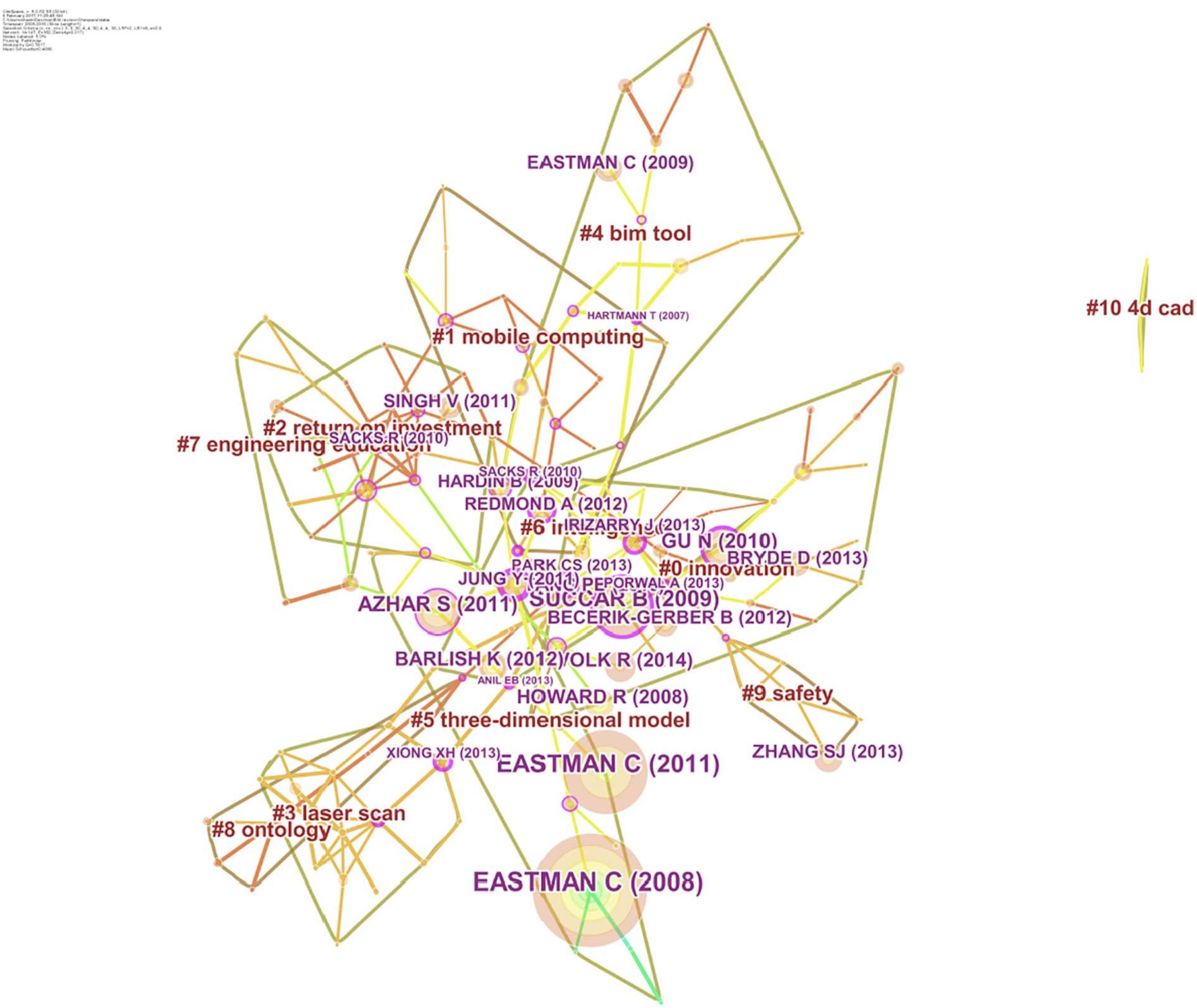

**Fig. 9.** Document co-citation network.

documents were: Park et al. [45] (centrality = 0.67), Jung and Joo [46] (centrality = 0.43), Irizarry et al. [47] (centrality = 0.37), Sacks et al. [48] (centrality = 0.33), Sacks et al. [49] (centrality = 0.31), and Anil et al. [50] (centrality = 0.31). They can be seen as the major intellectual turning points in BIM research, and most of them were included in the top 25 highly cited articles, as shown in Table 3. In addition, strong citation bursts were found at the five documents: Eastman et al. [44] (burst strength = 17.76, 2005–2013), Sacks et al. [51] (burst strength = 4.10, 2005–2010), Howard and Björk [42] (burst strength = 6.38, 2011–2014), Succar [3] (burst strength = 6.35, 2012–2013), and Cerovsek [13] (burst strength = 2.57, 2013–2014). These findings suggested that the citations of these documents increased significantly over a short period in the corresponding years. Both Cerovsek [13] and Howard and Björk [42] focused on the standards for data exchange and proposed frameworks to enhance BIM adoption, indicating that data exchange standardization was still a recent trend of BIM research.

A total of 10 significant co-citation clusters were identified based on the keywords of the documents cited in each cluster, by the log-likelihood ratio (LLR) algorithm. This is because the LLR method can select the best cluster labels in terms of uniqueness and coverage [52]. In Table 4, alternative labels with the second and third highest LLR scores are also shown, and clusters are sorted by size, i.e. the number of members. Thus, cluster #0 "innovation", with 21 members, was the largest one, while cluster #10 "4D CAD" was the smallest one, with only three members. In cluster #0, several yellow, orange and red links appeared, suggesting that these relationships were formed in 2014, 2015, and 2016, respectively. The top 25 highly cited articles were representative of clusters #0 to #9, but no article was within cluster #10. In addition, three articles in the top 25 list did not represent any co-citation clusters.

The silhouette metric measures the average homogeneity of a cluster [53]. For the clusters of similar sizes, a higher the silhouette score represents more consistency of the cluster members [52]. The silhouette scores of the clusters ranged from 0.731 to 1.000, suggesting that the members of each cluster were consistent enough. The average year of publication, i.e., mean year, of a cluster implies whether it is formed by recent documents or old documents. Thus, cluster #10 is formed by older documents than other clusters. In addition, the representative document of each cluster was the document with most co-citation frequency within a cluster. These representative documents influence the label of clusters and are worth attention.

Cluster #0 "innovation" has 21 members, and the representative document was published by Succar [3], who developed an innovative BIM framework for industry stakeholders. Cluster #1 had 16 members and was labeled with "mobile computing". The representative document was published by Redmond et al. [54], who attempted to employ cloud computing as an integration platform for improving the BIM usability experience for various disciplines in making key design decisions at a relatively early design stage. Cluster #2 had 15 members and was labeled with "return on investment". The representative document was published by Singh et al. [55], who proposed a framework of a BIM-based multi-disciplinary collaboration platform and found that cost savings may result from using a decision support system

**Table 4**
Co-citation clusters of BIM research 2005–2016.

| Cluster ID | Size | Silhouette | Cluster label (LLR) | Alternative label | Mean year | Representative documents |
|---|---|---|---|---|---|---|
| #0 | 21 | 0.841 | Innovation | BIM; critical success factor | 2011 | Succar [3] |
| #1 | 16 | 0.823 | Mobile computing | Cloud BIM; multi scale | 2011 | Redmond et al. [54] |
| #2 | 15 | 0.834 | Return on investment | Construction; building information model | 2010 | Singh et al. [55] |
| #3 | 15 | 0.922 | Laser scan | Reconstruction; performance control | 2010 | Bosché [56]; Xiong et al. [57] |
| #4 | 15 | 0.885 | BIM tool | Reality; workflow re-engineering | 2010 | Eastman et al. [58] |
| #5 | 15 | 0.932 | Three-dimensional model | Precast facade; fabrication engineering | 2009 | Eastman et al. [44] |
| #6 | 14 | 0.731 | Intelligence | construction simulation | 2011 | Tang et al. [12] |
| #7 | 10 | 0.943 | Engineering education | Three-dimensional model; information technology | 2011 | Grilo and Jardim-Goncalves [69] |
| #8 | 7 | 0.973 | Ontology | Linked data; semantic web technology | 2010 | Beetz et al. [73] |
| #9 | 6 | 0.976 | Safety | Construction safety rule and code checking; fall hazard prevention | 2012 | Zhang et al. [62] |
| #10 | 3 | 1.000 | 4D CAD | Building construction; automated generation | 2007 | Dawood and Mallasi [74] |

that may facilitate identification of various dependencies within the processes and between people and activities. In addition, clusters #3, #4 and #5 also had 15 members. Cluster #3 was labeled with “laser scan”. There are two representative documents, with a co-citation frequency of 12. Bosché [56] presented a new approach for automated recognition of project 3D CAD model objects in large laser scans. Xiong et al. [57] developed a new algorithm capable of modeling the main visible structural components of an indoor environment and automatically creating 3D building models from the data of laser scanners. Cluster #4 was labeled with “BIM tool”. Its representative document was published by Eastman et al. [58], who examined five major rule checking systems for assessing building designs and identified the major issues of these systems. Cluster #5 was labeled with “three-dimensional model”. The representative document was the BIM handbook published by Eastman et al. [44], which provided a full picture of BIM implementation for owners, managers, designers, engineers, and contractors.

## 4. Conclusions

BIM has transformed the AEC industry and attracted increasing attention from researchers and practitioners. This study provides a scientometric review to explore the status and trends of global BIM research. A total of 614 bibliographic records were collected from the WOS core collection database. Co-author analysis, co-word analysis and co-citation analysis were used to identify and visualize the status and trends of BIM research.

As for the contributions and influence of the lead researchers identified in the co-authorship and author co-citation analysis, Rafael Sacks, Xiangyu Wang and Charles M. Eastman were the top three most productive authors in the field, and Charles M. Eastman, Salman Azhar, Rafael Sacks obtained the top three most co-citations. Additionally, when comparing the most productive authors with the most influential authors, it was found that not all highly productive researchers have received the same high level of influence on BIM research. Some researchers (e.g., Rafael Sacks) without many publications can still receive a great number of co-citations and citation bursts. With respect to the distribution of journal articles on BIM, most of them originated from the USA, South Korea and China. In addition, Georgia Institute of Technology, Curtin University, and Kyung Hee University were the most productive institutions in the field of BIM. These countries and institutions also connected research activities between different countries and institutions.

Regarding the subject categories of BIM research, engineering, civil engineering and construction & building technology had the most publication records. However, environmental engineering, environmental sciences & ecology, business & economics, management, green & sustainable science & technology, and robotics were the emerging categories of focus in the recent years. In terms of the keywords, “construction”, “system” and “model” had the most frequency, while “visualization” and “industry foundation classes (IFC)” received the citation bursts in more recent years.

Several core journals have published most significant findings in BIM research, such as Automation in Construction, Advanced Engineering Informatics, the Journal of Computing in Civil Engineering, the Journal of Construction Engineering and Management, and the Journal of Information Technology in Construction. These journals also received high co-citation frequency and citation bursts in the past decade, indicating they had strong and continuous influence on BIM research. The majority of the top 25 highly cited articles were published in these journals, and Succar [3] received the most citations, according to the WOS citation metric.

According to the document co-citation analysis results, the two BIM handbooks published by Eastman et al. [31] and Eastman et al. [44] received the most co-citations. In the past five years, Eastman et al. [44], Howard and Björk [42], Succar [3] and Cerovsek [13] had citation bursts, and BIM data standardization was a recent research trend. Additionally, 10 co-citation clusters were identified based on the keywords associated with the analyzed documents. Thus, some hot topics related to BIM research can be summarized: mobile and cloud computing, laser scan, augmented reality, ontology, safety rule and code checking, semantic web technology, and automated generation.

This study provides valuable information for both researchers and practitioners in the field of BIM research. The key scholars and institutions, the state of the research field, and hot topics on BIM research were identified for researchers. In addition, this study will allow practitioners to obtain the key findings to enhance their BIM implementation and develop better BIM products. The scientometric review method can also be used to visualize the research trend in other topics.

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## References

[1] ISO, ISO 29481-1: 2016 Building Information Models - Information Delivery Manual - Part 1: Methodology and Format, International Organization for Standardization, Geneva, Switzerland, 2016.
[2] S. Azhar, Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry, Leadersh. Manag. Eng. 11 (3) (2011) 241–252.
[3] B. Succar, Building information modelling framework: a research and delivery foundation for industry stakeholders, Autom. Constr. 18 (3) (2009) 357–375.
[4] S. Azhar, M. Khalfan, T. Maqsood, Building Information Modeling (BIM): now and beyond, Australas. J. Constr. Econ. Build. 12 (4) (2012) 15–28.
[5] D. Bryde, M. Broquetas, J.M. Volm, The project benefits of building information modelling (BIM), Int. J. Proj. Manag. 31 (7) (2013) 971–980.
[6] McGraw Hill Construction, The Business Value of BIM in Australia and New Zealand, McGraw Hill Construction, Bedford, MA, 2014.
[7] E.A.L. Teo, G. Ofori, I.K. Tjandra, H. Kim, The potential of Building Information

Modelling (BIM) for improving productivity in Singapore construction, in: A.B. Raidén, E. Aboagye-Nimo (Eds.), 31st Annual ARCOM Conference, Association of Researchers in Construction Management, Lincoln, UK, 2015, pp. 661–670.

[8] Y. Arayici, C. Egbu, P. Coates, Building information modelling (BIM) implementation and remote construction projects: issues, challenges, and critiques, J. Inf. Technol. Constr. 17 (2012) 75–92.

[9] P. Wu, J. Wang, X. Wang, A critical review of the use of 3-D printing in the construction industry, Autom. Constr. 68 (2016) 21–31.

[10] L. Mahdjoubi, C. Moobela, R. Laing, Providing real-estate services through the integration of 3D laser scanning and building information modelling, Comput. Ind. 64 (9) (2013) 1272–1281.

[11] X. Wang, P.E. Love, M.J. Kim, C.-S. Park, C.-P. Sing, L. Hou, A conceptual framework for integrating building information modeling with augmented reality, Autom. Constr. 34 (2013) 37–44.

[12] P. Tang, D. Huber, B. Akinci, R. Lipman, A. Lytle, Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques, Autom. Constr. 19 (7) (2010) 829–843.

[13] T. Cerovsek, A review and outlook for a 'Building Information Model'(BIM): a multi-standpoint framework for technological development, Adv. Eng. Inform. 25 (2) (2011) 224–244.

[14] R. Volk, J. Stengel, F. Schultmann, Building Information Modeling (BIM) for existing buildings—literature review and future needs, Autom. Constr. 38 (2014) 109–127.

[15] D.J. Hess, Science Studies: An Advanced Introduction, New York University Press, New York, NY, 1997.

[16] L. Leydesdorff, S. Milojević, Scientometrics, in: J.D. Wright (Ed.), International Encyclopedia of Social and Behavioral Sciences, Elsevier, Oxford, UK, 2015, pp. 322–327.

[17] A. Pouris, A. Pouris, Scientometrics of a pandemic: HIV/AIDS research in South Africa and the world, Scientometrics 86 (2) (2011) 541–552.

[18] J. Song, H. Zhang, W. Dong, A review of emerging trends in global PPP research: analysis and visualization, Scientometrics 107 (3) (2016) 1111–1147.

[19] X. Zheng, Y. Le, A.P.C. Chan, Y. Hu, Y. Li, Review of the application of social network analysis (SNA) in construction project management research, Int. J. Proj. Manag. 34 (7) (2016) 1214–1225.

[20] W. Yi, A.P.C. Chan, Critical review of labor productivity research in construction journals, J. Manag. Eng. 30 (2) (2013) 214–225.

[21] Y. Ke, S. Wang, A.P.C. Chan, E. Cheung, Research trend of public-private partnership in construction journals, J. Constr. Eng. Manag. 135 (10) (2009) 1076–1086.

[22] C.C. Sullivan, Brace for BIM - the arrival of building information modeling seems inevitable. Are US architects ready for a revolution? Architecture 94 (4) (2005) 77–78.

[23] C. Chen, CiteSpace: A Practical Guide for Mapping Scientific Literature, Nova Science Publishers, 2016.

[24] B. Hjørland, H. Albrechtsen, Toward a new horizon in information science: domain-analysis, J. Assoc. Inf. Sci. Technol. 46 (6) (1995) 400–425.

[25] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, F. Herrera, Science mapping software tools: review, analysis, and cooperative study among tools, J. Am. Soc. Inf. Sci. Technol. 62 (7) (2011) 1382–1402.

[26] J. Kleinberg, Bursty and hierarchical structure in streams, Proceedings of the 8th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, ACM, Edmonton, Canada, 2002, pp. 91–101.

[27] C. Chen, S. Morris, Visualizing evolving networks: Minimum spanning trees versus pathfinder networks, IEEE Symposium on Information Visualization 2003, IEEE, Seattle, WA, 2003, pp. 67–74.

[28] L.C. Freeman, A set of measures of centrality based on betweenness, Sociometry 40 (1977) 35–41.

[29] M. Girvan, M.E. Newman, Community structure in social and biological networks, Proc. Natl. Acad. Sci. 99 (12) (2002) 7821–7826.

[30] C. Chen, CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature, J. Am. Soc. Inf. Sci. Technol. 57 (3) (2006) 359–377.

[31] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook—A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, second ed., John Wiley & Sons, Hoboken, NJ, 2011.

[32] B. Becerik-Gerber, F. Jazizadeh, N. Li, G. Calis, Application areas and data requirements for BIM-enabled facilities management, J. Constr. Eng. Manag. 138 (3) (2011) 431–442.

[33] P. Inyim, J. Rivera, Y. Zhu, Integration of building information modeling and economic and environmental impact analysis to support sustainable building design, J. Manag. Eng. 31 (1) (2014) A4014002.

[34] P. Wu, B. Xia, X. Zhao, The importance of use and end-of-life phases to the life cycle greenhouse gas (GHG) emissions of concrete - a review, Renew. Sust. Energ. Rev. 37 (2014) 360–369.

[35] P. Wu, B. Xia, J. Pienaar, X. Zhao, The past, present and future of carbon labelling for construction materials-a review, Build. Environ. 77 (2014) 160–168.

[36] S. Azhar, W.A. Carlton, D. Olsen, I. Ahmad, Building information modeling for sustainable design and LEED® rating analysis, Autom. Constr. 20 (2) (2011) 217–224.

[37] B.G. Hwang, X. Zhao, L.L.G. Tan, Green building projects: schedule performance, influential factors and solutions, Eng. Constr. Archit. Manag. 22 (3) (2015) 327–346.

[38] Y.-C. Lin, Use of BIM approach to enhance construction interface management: a case study, J. Civ. Eng. Manag. 21 (2) (2015) 201–217.

[39] E.M. Wetzel, W.Y. Thabet, The use of a BIM-based framework to support safe facility management processes, Autom. Constr. 60 (2015) 12–24.

[40] C. Feng, Y. Xiao, A. Willette, W. McGee, V.R. Kamat, Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites, Autom. Constr. 59 (2015) 128–138.

[41] H. Small, Co-citation in the scientific literature: a new measure of the relationship between two documents, J. Assoc. Inf. Sci. Technol. 24 (4) (1973) 265–269.

[42] R. Howard, B.-C. Björk, Building information modelling–Experts' views on standardisation and industry deployment, Adv. Eng. Inform. 22 (2) (2008) 271–280.

[43] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, Autom. Constr. 19 (8) (2010) 988–999.

[44] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook—A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, second ed., John Wiley & Sons, Hoboken, NJ, 2008.

[45] C.-S. Park, D.-Y. Lee, O.-S. Kwon, X. Wang, A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template, Autom. Constr. 33 (2013) 61–71.

[46] Y. Jung, M. Joo, Building information modelling (BIM) framework for practical implementation, Autom. Constr. 20 (2) (2011) 126–133.

[47] J. Irizarry, E.P. Karan, F. Jalaei, Integrating BIM and GIS to improve the visual monitoring of construction supply chain management, Autom. Constr. 31 (2013) 241–254.

[48] R. Sacks, L. Koskela, B.A. Dave, R. Owen, Interaction of lean and building information modeling in construction, J. Constr. Eng. Manag. 136 (9) (2010) 968–980.

[49] R. Sacks, M. Radosavljevic, R. Barak, Requirements for building information modeling based lean production management systems for construction, Autom. Constr. 19 (5) (2010) 641–655.

[50] E.B. Anil, P. Tang, B. Akinci, D. Huber, Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data, Autom. Constr. 35 (2013) 507–516.

[51] R. Sacks, C.M. Eastman, G. Lee, Parametric 3D modeling in building construction with examples from precast concrete, Autom. Constr. 13 (3) (2004) 291–312.

[52] C. Chen, The CiteSpace Manual (available from), http://cluster.ischool.drexel.edu/~cchen/citespace/CiteSpaceManual.pdf, (2014).

[53] P.J. Rousseeuw, Silhouettes: a graphical aid to the interpretation and validation of cluster analysis, J. Comput. Appl. Math. 20 (1987) 53–65.

[54] A. Redmond, A. Hore, M. Alshawi, R. West, Exploring how information exchanges can be enhanced through Cloud BIM, Autom. Constr. 24 (2012) 175–183.

[55] V. Singh, N. Gu, X. Wang, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, Autom. Constr. 20 (2) (2011) 134–144.

[56] F. Bosché, Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction, Adv. Eng. Inform. 24 (1) (2010) 107–118.

[57] X.H. Xiong, A. Adan, B. Akinci, D. Huber, Automatic creation of semantically rich 3D building models from laser scanner data, Autom. Constr. 31 (2013) 325–337.

[58] C. Eastman, J.-m. Lee, Y.-s. Jeong, J.-k. Lee, Automatic rule-based checking of building designs, Autom. Constr. 18 (8) (2009) 1011–1033.

[59] J.D. Goedert, P. Meadati, Integrating construction process documentation into building information modeling, J. Constr. Eng. Manag. 134 (7) (2008) 509–516.

[60] C.S. Dossick, G. Neff, Organizational divisions in BIM-enabled commercial construction, J. Constr. Eng. Manag. 136 (4) (2010) 459–467.

[61] P. Geyer, Component-oriented decomposition for multidisciplinary design optimization in building design, Adv. Eng. Inform. 23 (1) (2009) 12–31.

[62] S.J. Zhang, J. Teizer, J.K. Lee, C.M. Eastman, M. Venugopal, Building Information Modeling (BIM) and safety: automatic safety checking of construction models and schedules, Autom. Constr. 29 (2013) 183–195.

[63] B. Becerik-Gerber, F. Jazizadeh, N. Li, G. Calis, Application areas and data requirements for BIM-enabled facilities management, J. Constr. Eng. Manag. 138 (3) (2012) 431–442.

[64] G. Lee, R. Sacks, C.M. Eastman, Specifying parametric building object behavior (BOB) for a building information modeling system, Autom. Constr. 15 (6) (2006) 758–776.

[65] J.E. Taylor, P.G. Bernstein, Paradigm trajectories of building information modeling practice in project networks, J. Manag. Eng. 25 (2) (2009) 69–76.

[66] I. Brilakis, L. Manolis, R. Sacks, S. Savarese, S. Christodoulou, J. Teizer, A. Makhmalbaf, Toward automated generation of parametric BIMs based on hybrid video and laser scanning data, Adv. Eng. Inform. 24 (4) (2010) 456–465.

[67] J.P. Zhang, Z.Z. Hu, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies, Autom. Constr. 20 (2) (2011) 167–180.

[68] T. Hartmann, H. van Meerveld, N. Vossebeld, A. Adriaanse, Aligning building information model tools and construction management methods, Autom. Constr. 22 (2012) 605–613.

[69] A. Grilo, R. Jardim-Goncalves, Value proposition on interoperability of BIM and collaborative working environments, Autom. Constr. 19 (5) (2010) 522–530.

[70] Y.S. Jeong, C.M. Eastman, R. Sacks, I. Kaner, Benchmark tests for BIM data exchanges of precast concrete, Autom. Constr. 18 (4) (2009) 469–484.

[71] K. Barlish, K. Sullivan, How to measure the benefits of BIM - a case study approach, Autom. Constr. 24 (2012) 149–159.

[72] J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Build. Environ. 60 (2013) 81–92.

[73] J. Beetz, J. Van Leeuwen, B. De Vries, IfcOWL: a case of transforming EXPRESS schemas into ontologies, Artif. Intell. Eng. Des. Anal. Manuf. 23 (1) (2009) 89–101.

[74] N. Dawood, Z. Mallasi, Construction workspace planning: assignment and analysis utilizing 4D visualization technologies, J. Comput. Aided Civ. Infrastruct. Eng. 21 (7) (2006) 498–513.