BIM CRITICAL SUCCESS FACTORS IN DIFFERENT LIFE-CYCLE PHASES: A REVIEW EXPLORING THE TECHNOLOGY, PEOPLE, AND PROCESS BIM CATEGORIES

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Abstract: This study aims to draw the scenario of the BIM research field and investigates the relationship of BIM categories (technology, process, and people) with critical success factors, stratified in four life cycle phases (Design, Pre-Construction, Construction, and Operation). The research design is a literature review (SLR) performed through bibliometrics and content analysis. The findings showed the theme evolution based on two motor themes that stood out, artificial intelligence and construction supply chain; three niche themes emerged, data exchange, lean construction, and smart contracts. Finally, we verified the lack of studies focusing on enhancing BIM research related to the Process and People BIM categories once the Technology category has been more studied in the field.

Keywords: BIM, Building Information Modeling, Critical success factors, Building life cycle, Pre-construction phase.

1. INTRODUCTION

BIM efficiently manages data exchanges throughout the built asset life cycle, including the operational phase using BIM-based tools, workflows, and standards (Patacas et al., 2020). The building life cycle (BLC) comprises three phases: Design, Construction, and Operation (Succar, 2009). In each phase, different critical success factors (CSFs) emerge, with distinctive effects through the four BLC phases (BLC) (Antwi-Afari et al., 2018).

The success of the BIM approach relies on three main categories: technology, people, and process (Liu et al., 2017). These categories are complementary, synergistic, and can be implemented independently. However, the lack of any of these dimensions will result in a more negligible effect on successful project collaboration during BIM implementation.

This study, therefore, aims to narrow these gaps by answering the following research questions: RQ1) How has BIM literature evolved in the last decades? and RQ2) What are the BIM critical success factors (CSFs), considering BLC phases and BIM categories? The study objective is to draw a scene of the BIM research field, investigating the relationship of the BIM CFSs, BIM categories (technology, process, and people), and BLC phases.

This study contributes by depicting the body of literature on BIM, mapping the core authors, keywords, and journals, explaining the current theme evolution and intellectual structure, and identifying patterns, gaps, and future trends. Second, we focused on identifying how the BIM CSFs relate to the categories: technology, process, and people. We understand there is still a gap between design and construction phases due to construction fragmentation. This study included the pre-construction phase by considering pre-construction as a relevant phase in the built life cycle asset. As a result, we categorized the CSFs into four main phases (Design, Pre-construction, Construction, and Operation).

Our paper is structured as follows: Section 2 outlines the research methodology detailing the sampling process and data analysis developed through bibliometrics and content analysis. Section 3 presents findings, and Section 4 summarizes the discussion and future agenda. Section 5 presents the research contributions and limitations and proposes future work opportunities.

2 RESEARCH METHODOLOGY

The research methodology used to address the research questions was a systematic literature review (SLR). The SLR consists in identifying and synthesizing all the research evidence available concerning a specific subject in organized, transparent, and replicable procedures (Littell et al., 2008; Victor, 2008) in three main phases: planning the review, conducting the review, and reporting the review (Kitchenham, 2004). For meeting the research goal, we performed the SLR by applying the following methods: bibliometrics, content analysis, and cross-tabulation of content analysis. The research methodology was developed in five main steps as shown in Figure 1.

FIGURE 1: RESEARCH METHODOLOGY STEPS

2.1 Sampling Process

A two-step sample process was developed, first in articles and reviews from the Web of Science database, then a backward snowballing towards the key references. The sampling process started with an initial search in the Web of Science core collection database. We conducted the first search in February 2021 using the strings ''Building Information Modeling'', ''BIM'', ''Building Information Modelling'', and the logical operator "OR" between terms, which yielded 13,238 results. To select only papers from the field of research, we applied the following filters: 1) Web of Science category: "construction building technology" and "architecture; 2) Document types: "articles" and "reviews" (as in peer-reviewed); 3) Research area: "construction building technology" and "architecture". As a result of this filtering process, we obtained 1,378 publications published from 2000 to 2020 for the final sample.

The sampling process was designed to develop a qualitative approach via content analysis and a quantitative approach through bibliometrics and cross-tabulation of the content analysis. The quantitative approach concentrated on running the data extracted from the Web of Science database through network analysis software. For the qualitative approach, we applied another filter to find a reasonable sample. Due to the large sample of articles, we considered selecting 50% of the most cited publications by annual average.

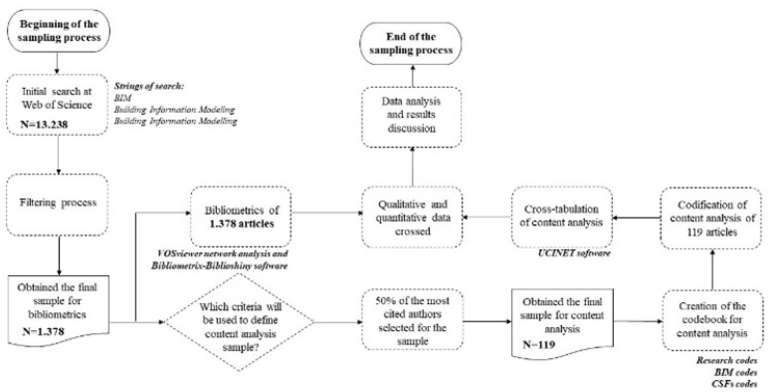

FIGURE 2: SAMPLING PROCESS

The 1,378 papers corresponded to 2,993 citations/per year. Thus, choosing 50% of 2,993 citations/per year resulted in 119 papers. After this final filtering process, we created a codebook for content analysis.

Subsequently, we analyzed the 119 articles qualitatively and crossed quantitative and qualitative data to obtain the results. Finally, we concentrated on data analysis and results from the discussion. Figure 2 shows how we developed the sampling process for data collection.

2.2 BIBLIOMETRICS

For drawing a scenario of the BIM research field through bibliometrics, we examined the scientific database to analyze the main patterns and important academic studies based on citation analysis as a proxy of impact (Takey & Carvalho, 2016). Bibliometrics is helpful to visualize the relevance and the impact of themes, articles, authors, and sources in the literature aligned with RQ1. Besides, network analysis facilitates mapping the relationship between keywords, authors, and references, which helps obtain the relationship among the variables (Carvalho et al., 2013).

To visualize and analyze the BIM scientific knowledge in the literature, we explored a sample of 1,378 papers, performing bibliometric analysis through VOSviewer software (version 1.6.13 for Windows) and Bibliometrix-Biblioshiny software (Aria & Cuccurullo, 2017).

We characterized the sample demographics in the initial step by identifying the most relevant authors, documents, sources, countries, and institutions (Paul & Criado, 2020), with the aim of descriptive statistics and Bibliometrix-Biblioshiny software, drawing sources dynamics, and top authors' production over time.

Before performing this analysis, we sorted the metadata, particularly regarding keywords; for example, we identified nine different keywords for BIM (BIM; Building Information Model; Building Information Model (BIM); Building Information Models; Building Information Model (BIM); Building Information Modeling; Building Information Modeling (BIM); Building Information Modelling; Building Information Modelling (BIM)).

At the second step, we mapped the relationship among authors, references, and sources with the VOSviewer software, performing three types of networks: co-citation network, co-occurrence of keywords, and sources. Then, in Bibliometrix-Biblioshiny software, we performed the conceptual structure and intellectual structure analysis (Ramos-Rodríguez & Ruíz-Navarro, 2004), running thematic mapping, thematic evolution in selected time slices, and a historiographic analysis.

2.3 CONTENT ANALYSIS

According to Duriau et al. (2007) ''content analysis allows rendering the rich meaning associated with organizational documents combined with powerful quantitative analysis''. In other words, content analysis is a structured and systematic technique for compressing several words of text into a volume of textual data in an organized manner to identify the focus of the subject matter and to observe emerging patterns in the literature (Giannantonio, 2010; Weber, 1990). For content analysis, we structured a codebook based on two main clusters of codes, namely: BIM codes and CSFs (critical success factors) related to the building life cycle phases (BLC) codes.

To develop the BIM codes, we extracted the top 10 papers of the sample from the Web of Science database. Then, we intensely studied each paper to create the BIM codes and then improved them during the content analysis process. The code analysis allows investigating the relationship between codes through cross-tabulation, network analysis, and core-periphery analysis, performed with the IBM SPSS software, UCINET6, and Netdraw software (Borgatti et al., 2002).We created fourteen (14) BIM codes based on the 10 most cited papers, as illustrated in Table 1.

To create the CSFs related to BLC phases codes, we first defined four main phases, Design, Pre-construction, Construction, and Operation, as aforementioned in the introduction. Then, based on a summary of 34 CSFs for BIM implementation found in literature and gathered by Antwi-Afari et al. (2018), we took the 34CSFs and distributed them into, the four main phases based on our knowledge categorizing each CSF into each BLC phase.

TABLE 1: TOP 10 MOST CITED PUBLICATIONS OF THE SAMPLE (1 IS THE MOST CITED AND 10 THE LEAST CITED)

Paper order	Tittle	Authors	Journal
1	Building information modeling (BIM) for existing buildings – Literature review and future needs	(Volk et al., 2014)	Automation in Construction
2	Building information modeling framework: A research and delivery foundation for industry stakeholders	(Succar, 2009)	Automation in Construction
3	The project benefits of building information modeling (BIM)	(Bryde et al., 2013)	International Journal of Project Management
4	Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules	(S. Zhang et al., 2013)	Automation in Construction
5	Application areas and data requirements for BIM-enabled facility management	(Klein et al., 2012)	Journal of Construction Engineering and Management
6	Enhancing environmental sustainability over building life cycles through green BIM: A review	(Wong & Zhou, 2015)	Automation in Construction
7	A scientometric review of global BIM research: Analysis and visualization	(Zhao, 2017)	Automation in Construction
8	Mapping the managerial areas of building information modeling (BIM) using scientometric analysis	(He et al., 2017)	nternational Journal of Project Management
9	Understanding the effects of BIM on collaborative design and construction: An empirical study in China	(Liu et al., 2017)	International Journal of Project Management
10	Identifying and contextualizing the motivations for BIM implementation in construction projects: An empirical study in China	(Cao et al., 2017)	International Journal of Project Management

3 RESULTS

3.1 Sample Demographics

The annual number of publications has significantly increased publication patterns since 2009, which could be explained by the globally rising trend of BIM adoption. The publications surveyed were published from 2002 to 2021 (see Figure 3).

Based on Web of Science data, we observed the number of publications has massively risen from under 40 to more than 280 publications in 10 years (2010-2020), as illustrated in Figure 3a. Furthermore, there was a relevant expansion in the number of citations in the last 10 years, starting from nearly 100 citations/year in 2010 and growing sharply up to 8,000 citations/year in 2020 as observed in Figure 3b.

In our sample, five countries stood out with the highest number of publications and citations. The most productive country is the USA (549 articles), followed by China (470), the United Kingdom (315), Australia (224), and South Korea (190). However, in the top 5 most productive affiliations in the sample, the first one is Curtin University in Australia, three are Chinese universities (The Hong Kong Polytechnic University, University of Hong Kong, and Tsinghua University) and one from South Korea (Kyung Hee University).

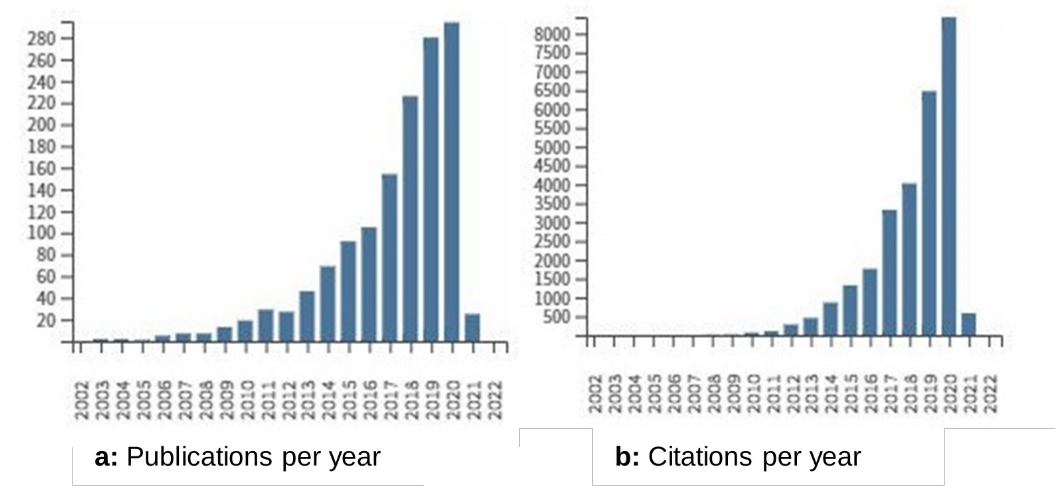

FIGURE 3: PUBLICATIONS EVOLUTION PER YEAR

3.2 Bibliometrics

3.2.1 Key authors, documents, and references

For depicting the intellectual structure, we draw the historiographic, which explores the paths through the top 30 documents, applying the local citation score (Schöggl et al., 2020). Figure 4 shows the historiographic developed from 2006 to 2017, starting with (G. Lee et al., 2006) and finishing with (Santos et al., 2017).

After identifying the top documents, we surveyed the core authors, considering both productivity and citations over time (see Figure 5). Note that while some authors stood out in recent years, such as Hosseini and Edwards, others have consistently influenced the field for more than a decade such as Eastman, Sacks, and Lee.

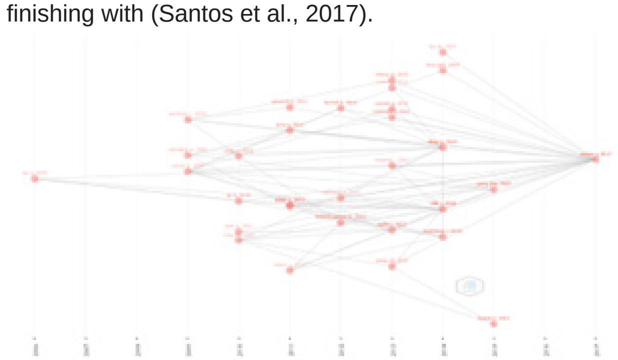

FIGURE 4: NUMBER OF NODES = 30. (NOTE: EXTRACTED USING BIBLIOSHINY).

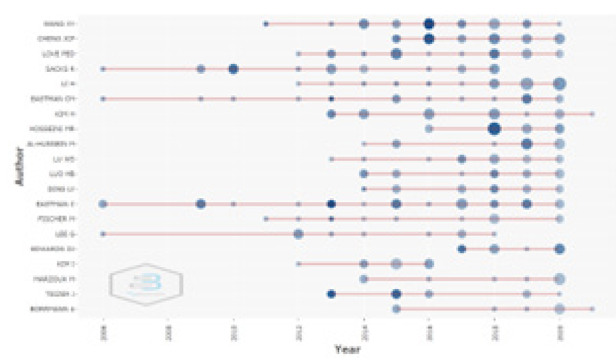

FIGURE 5: TOP-AUTHORS' PRODUCTION OVER TIME. (NOTE: EXTRACTED USING BIBLIOSHINY).

Legend:
Lines represent the authors' timeline.
Bubble size is proportional to the number of documents.
Color intensity is proportional to the total citations per year.

According to Carvalho et al. (2013), co-citation networks allow observing the relatedness of items based on the number of times they are cited together in the sample. The network permits us to understand the affinities of researchers, the intellectual structures of the knowledge body, and how research groups are related to each other. A co-citation network is shown in Figure 6, where each node represents a reference and the links between references denote the collaboration established through the co-citation in the articles.

The most cited reference in the co-citation network analysis was C. M. Eastman et al. (2011) (green cluster) with 228 citations, who developed The BIM Handbook: A Guide to Building Information Modeling. The top-five following authors were: Azhar (2011); Succar (2009); Volk et al. (2014); S. Zhang et al. (2013) and C. M. Eastman et al. (2008). Other significant cited references were Becerik-Gerber et al. (2012); C. Eastman et al. (2009) and Azhar et al. (2011).

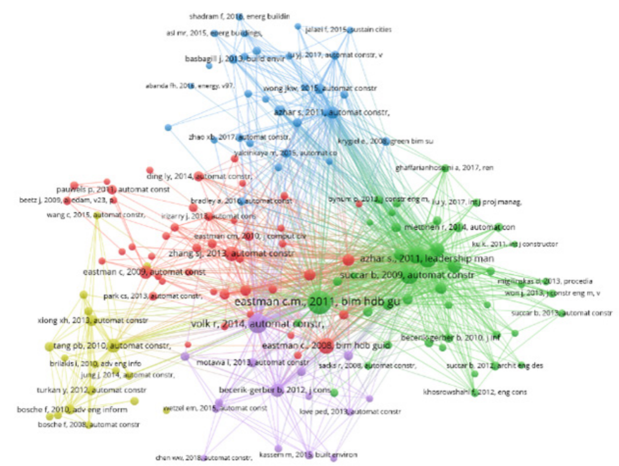

FIGURE 6: CO-CITATION NETWORK. (NOTE: APPLYING VOS VIEWER SOFTWARE)

Thus, the pattern of the relationship among top authors, references, and keywords are depicted in Figure 7. It could be noted that most authors explore BIM general themes and Industry Foundation Classes (IFC). However, facility management, Edwards and Marzouk), sustainability (Chan), life-cycle assessment (LCA) (Fischer), and virtual reality (Sacks) are explored only by a few authors. (Based on the local cited reference score, the most influential reference is C. M. Eastman et al. (2008), as mentioned before.

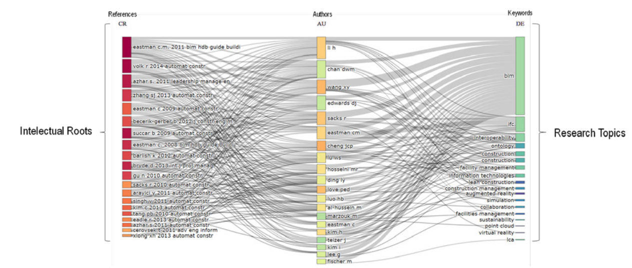

FIGURE 7: RELATIONSHIP AMONG TOP AUTHORS, CITED REFERENCES AND KEYWORDS

3.2.2 Trend topics and thematic evolution

According to Zhao (2017), ''keywords present the core content of articles and show the development of research topics over time''. During the VOSviewer configuration process, we chose full counting and ''Author keywords'' with a minimum of five occurrences by keyword representing 4,865 keywords; 347 met the thresholds.

Figure 8 shows the most high-frequency keywords were BIM, design, management, construction, system, implementation, performance. BIM (red node) appeared as the main node of the network followed by design, construction, and management (blue nodes). Building information modeling (orange and light blue nodes) represented a noticeable number of total link strengths and occurrences. According to Yalcinkaya and Singh (2015), Building Information Modeling (BIM) has emerged as one of the key streams in the construction industry, and received a considerable amount of attention by researchers within the last decade, with an accelerated increase in the number of publications.

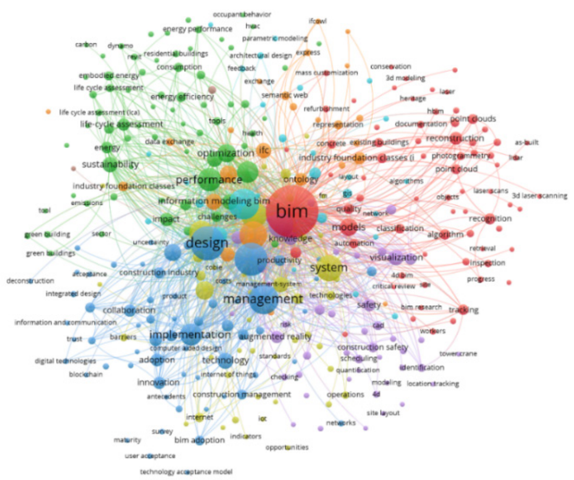

FIGURE 8: CO-OCCURRENCE NETWORK. (NOTE: APPLYING VOSVIEWER SOFTWARE)

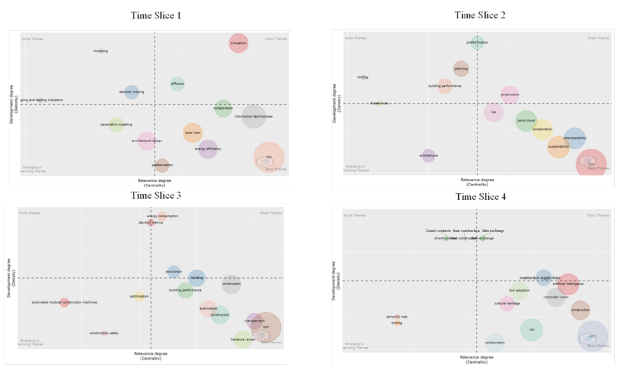

FIGURE 9: THEMATIC EVOLUTION OVER TIME (NOTE: EXTRACTED USING BIBLIOSHINY).

To identify the core concepts and topics over time, we performed a Thematic Evolution analysis using Biblioshiny, exploring asymmetric time slices because the literature evolution has had a craggy curve in recent years, as shown in Figure 9.

New topics have emerged as niche themes lately, particularly data exchange, lean construction, and smart contracts, while two motor themes stood out, artificial intelligence and construction supply chain.

3.3 Content Analysis

3.3.1 Understanding the BIM approach in Academia

BIM codes analysis first started with the understanding of BIM research areas of study in the field. We established eleven major areas of study to classify the field of BIM research of each article. Table 2 summarizes a descriptive statistical analysis of BIM research (code B1) which is presented by number and subcode name (research area); number and percentage of the paper's occurrence classified into each research area, and the authors corresponded to each BIM research area.

TABLE 2: BIM RESEARCH DESCRIPTIVE STATISTICAL ANALYSIS

Codes	BIM research subcodes	N. of papers	%	Authors
R1	BIM ontology (linked data; semantic web technology)	14	12%	(Deng et al., 2016; Karan & Irizarry, 2015; S.-K. Lee et al., 2014; X. Li et al., 2017; C.-S. Park et al., 2013; P. Pauwels et al., 2011; Pieter Pauwels et al., 2017; Santos et al., 2017; Succar, 2009; Succar & Kassem, 2015; Succar et al., 2013; Vanlande et al., 2008; Yalcinkaya & Singh, 2015; S. Zhang, Boukamp, et al., 2015)
R2	BIM in the AEC education	4	3%	(X. Li et al., 2017; Santos et al., 2017; Yalcinkaya & Singh, 2015; Zhao, 2017)
R3	BIM in the AEC industry	25	21%	(Arayici et al., 2011; Barlish & Sullivan, 2012; Bradley et al., 2016; Cao et al., 2014; Cao et al., 2015; Chen & Luo, 2014; Eadie et al., 2013; Franz et al., 2017; Gu & London, 2010; Hartmann et al., 2012; Hosseini et al., 2018; Y. Jung & Joo, 2011; G. Lee et al., 2006; X. Li et al., 2017; Love et al., 2015; Miettinen & Paavola, 2014; Monteiro & Martins, 2013; Porwal & Hewage, 2013; Sacks, Koskela, et al., 2010; Santos et al., 2017; Singh et al., 2011; Succar, 2009; Succar & Kassem, 2015; Succar et al., 2013; S. Zhang, Boukamp, et al., 2015)
R4	Safety (construction safety rule and code checking)	18	15%	(Ding et al., 2014; Dossick & Neff, 2010; C. Eastman et al., 2009; W. Fang et al., 2018; Y. Fang et al., 2016; Guo et al., 2017; K. Kim et al., 2016; X. Li et al., 2017; C.-S. Park & Kim, 2013; JeeWoong Park et al., 2017; Santos et al., 2017; Solihin & Eastman, 2015; Yalcinkaya & Singh, 2015; J. Zhang & Hu, 2011; S. Zhang et al., 2013; S. Zhang, Teizer, et al., 2015; Zhou et al., 2012)
R5	Sustainability (energy, acoustic, energy simulation)	18	15%	(Akbarnezhad et al., 2014; Azhar et al., 2011; Basbagill et al., 2013; Bynum et al., 2013; Doan et al., 2017; El-Diraby et al., 2017; Iddon & Firth, 2013; Ilhan & Yaman, 2016; Jalaei & Jrade, 2015; X. Li et al., 2017; S. Liu et al., 2015; Lu et al., 2017; Santos et al., 2017; Schlueter & Thesseling, 2009; Shadram et al., 2016; Soust-Verdaguer et al., 2017; Wong & Zhou, 2015; Yalcinkaya & Singh, 2015)
R6	Facility management (existing buildings, reconstruction, performance control)	13	11%	(Becerik-Gerber et al., 2012; X. Li et al., 2017; Motamedi et al., 2014; Pärn et al., 2017; Pishdad-Bozorgi et al., 2018; Santos et al., 2017; Volk et al., 2014; Wetzel & Thabet, 2015; Yalcinkaya & Singh, 2015)
R7	BIM technology applications (Laser scanning, Virtual reality/UAV)	14	12%	(Bosché et al., 2015; Du et al., 2018; J. Jung et al., 2014; M.-K. Kim et al., 2015; M.-K. Kim et al., 2016; Klein et al., 2012; X. Li et al., 2017; C.-S. Park et al., 2013; Santos et al., 2017; Tang et al., 2010; C. Wang et al., 2015; X. Wang et al., 2013; Xiong et al., 2013; Yalcinkaya & Singh, 2015)
R8	H-BIM (Historic Building Information Modeling)	4	3%	(Bruno et al., 2018; X. Li et al., 2017; Santos et al., 2017; Yalcinkaya & Singh, 2015)
R9	Innovation (3D-priting, critical success factor, Lean construction, LPS)	10	8%	(Chien et al., 2014; Dave et al., 2016; C. Z. Li et al., 2018; X. Li et al., 2017; Love et al., 2013; Sacks, Radosavljevic, et al., 2010; Santos et al., 2017; Son et al., 2015; Wu et al., 2016; Yalcinkaya & Singh, 2015)
R10	Intelligence (interoperability, building performance, construction simulation)	31	26%	(Asl et al., 2015; Borrmann et al., 2015; Deng et al., 2016; Dong et al., 2014; Gerrish et al., 2017; Göçer et al., 2015; Goedert & Meadati, 2008; Grilo & Jardim-Goncalves, 2010; Habibi, 2017; Ham & Golparvar-Fard, 2015; Irizarry et al., 2013; Karan & Irizarry, 2015; C. Kim et al., 2013; H. Kim et al., 2013; J. B. Kim et al., 2015; Kumar & Cheng, 2015; S.-K. Lee et al., 2014; N. Li et al., 2014; X. Li et al., 2017; H. Liu et al., 2015; Negendahl, 2015; Jaehyun Park & Cai, 2017; Pieter Pauwels et al., 2017; Pinheiro et al., 2018; Redmond et al., 2012; Sacks et al., 2017; Santos et al., 2017; Vanlande et al., 2008; C. Wang et al., 2015; H. Wang & Zhai, 2016; Yalcinkaya & Singh, 2015; Zhong et al., 2017)
R11	Mobile computing (BIM cloud, multi scale)	8	7%	(Anil et al., 2013; Davies & Harty, 2013; Han & Golparvar-Fard, 2015, 2017; X. Li et al., 2017; Santos et al., 2017; X. Wang et al., 2014; Yalcinkaya & Singh, 2015)
% in 119 articles				

From cross-tabulation, we observed a strong relationship between BIM ontology (R1) and BIM in the AEC industry (R3), and BIM ontology (R1) and Intelligence (R10). Additionally, there was a significant relationship between BIM ontology (R1) and Safety (R4), and BIM ontology (R1) and BIM technologies applications (R4) as illustrated in Figure 10.

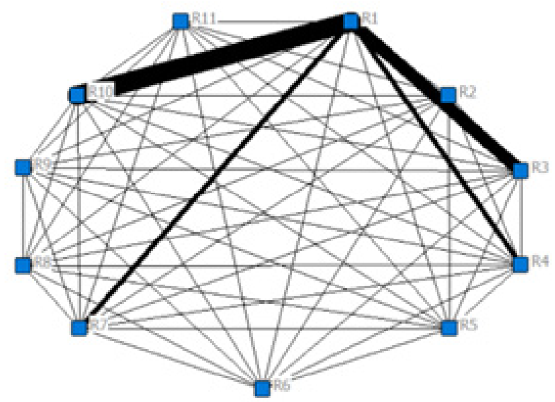

FIGURE 10: BIM RESEARCH NETWORK (NOTE: APPLYING THE UCINET SOFTWARE)

After analyzing BIM research fields, we focused on understanding BIM adoption classified into macro, meso, and micro-categories. Based on Liu et al. (2017), we first classified BIM macro-categories named by Technology, People and Process focused issues. Second, we subdivided each macro-category into meso categories. Third, we subdivided each meso-category into macro-categories as can be seen in Table 3, Table 4, and Table 5.

TABLE 3: BIM MACRO CATEGORIES DESCRIPTIVE STATISTICAL ANALYSIS

Code (B2)	BIM macro-category subcodes	N. of papers	%
MacC1	Technology-focused issues	94	79%
MacC2	People-focused issues	13	11%
MacC3	Process-focused issues	50	42%

TABLE 4: BIM MESO-CATEGORIES DESCRIPTIVE STATISTICAL ANALYSIS

Code(B3)	BIM meso-category subcodes	N. of papers	%
MesC1a	IT capacity	79	66%
MesC1b	Technology management	58	49%
MesC2a	Attitude and behavior	7	6%
MesC2b	Role taking	11	9%
MesC3a	Communication	35	29%
MesC3b	Leadership	3	3%
MesC3c	Trust	16	13%
MesC3d	Learning and experience	13	11%

TABLE 5: BIM MICRO-CATEGORIES DESCRIPTIVE STATISTICAL ANALYSIS

Code (B4)	BIM micro-category subcodes	N. of papers	%
MicC1a1	software functionality	61	51%
MicC1a2	software immaturity	8	7%
MicC1a3	compatibility	34	29%
MicC1b1	model creation management	14	12%
MicC1b2	model sharing management	48	40%
MicC2a1	designer attitude	6	5%
MicC2a2	reluctance to initiate new works flows	5	4%
MicC2b1	The emergence of new roles	5	4%
MicC2b2	confliction obligations	7	6%
MicC3a1	information exchange	22	18%
MicC3a2	direct access to collaboration	9	8%
MicC3a3	organizational structure	18	15%
MicC3a4	business purposes	11	9%
MicC3a5	different requirements	3	3%
MicC3b1	third party as a leader	1	1%
MicC3b2	direct participants as leaders	3	3%
MicC3c1	trust effects	12	10%
MicC3c2	affecting trust	2	2%
MicC3c3	experience	5	4%
MicC3c1	inadequate BIM skills	6	5%
MicC3d2	learning approach	7	6%
MicC3d3	organizational learning	7	6%
% in 119 articles			

The descriptive statistical analysis showed Technology-focused issues (MacC1) were the most BIM macro-category studied with 79%, followed by Process-focused issues (MacC3) with 42%, and People-focused issues (MacC2) with 11% of our sample. In the BIM meso-categories, we noticed the most representative ones were: IT capacity (66%), Technology management (49%), and Communication (29%). Concerning the BIM macro-categories, we observed Software functionality (51%), Model sharing management (40%), and Compatibility (29%) as the most studied of the sample.

From the cross-tabulation, we recognized a stronger network between Technology (MacC1) and Process (MacC3) in comparison to the Technology and People (MacC2) network, and the Process and People network as illustrated in Figure 11.

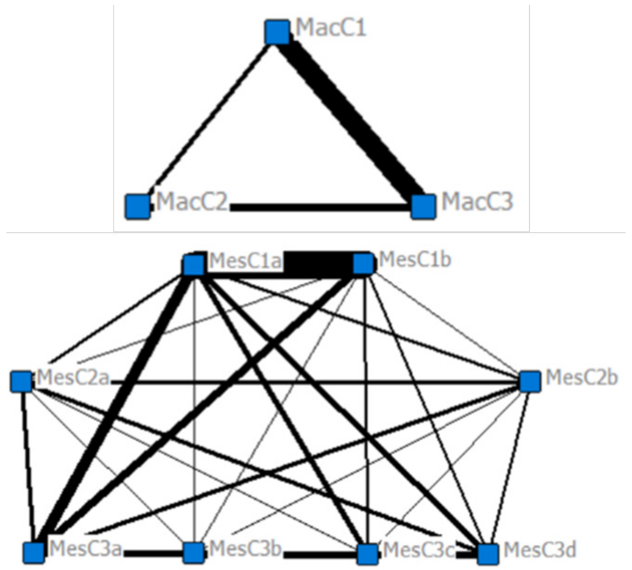

FIGURE 11: BIM MACRO-CATEGORIES AND MESO-CATEGORIES NETWORK (NOTE: APPLYING UCINET SOFTWARE)

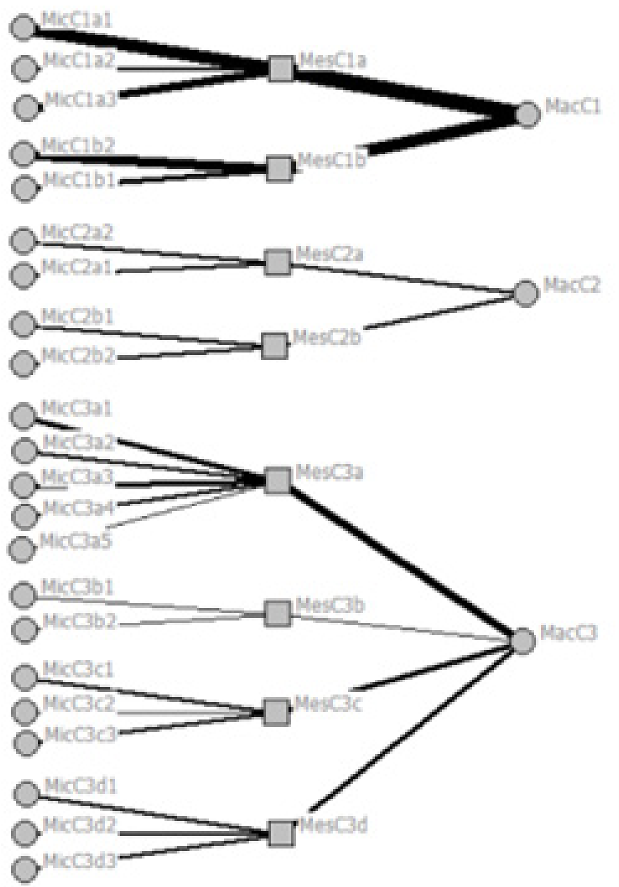

FIGURE 12: BIM MACRO, MESO, AND MICRO-CATEGORIES CODE TREE (NOTE: APPLYING UCINET SOFTWARE)

In the BIM meso-categories network, we primarily observed a robust relationship between IT capacity (MesC1a) and Technology management (MesC1b) and a considerable relationship between these two meso-categories with Communication (MesC3a).

Figure 12 shows a code tree analysis between BIM macro, meso, and micro-categories. As previously observed in the descriptive statistical code analysis, Technology-focused issues (MacC1) composed the most notorious BIM macro-category compared to People and Process-focused issues. From the code tree analysis, we identified IT capacity (MicC1a) and Technology management (MicC1b) as the most relevant meso-categories and Software functionality (MicC1a1) and Model sharing management (MicC1b2) as the most representative macro-categories related to Technology-focused issues (MacC1). Communication (MesC3a) represented the most mentioned meso-category and Information exchange (MicC3a1) and Organizational structure (MicC3a3), the most studied macro-categories related to Process-focused issues (MacC3).

3.3.2 BIM macro-categories relationship with CSFs in the BLC phases

Since our secondary research goal was to investigate the correlation of BIM macro-categories with CSFs in the building life cycle phases, we crossed technology, process, and people as BIM macro-categories codes with the four CSFs codes using UCINET software. The CSF codes were categorized into the design, pre-construction, construction, and operation phases as previously defined in the methodology research.

The analysis showed Process (MacC3) BIM macro-category has more significant correlations with CSFs codes than to Technology and People. Figure 13 illustrates the relationship between Technology with CFS codes in each building life cycle phase. The network analysis showed stronger correlations between CSFs D12 with the design phase; CSFs PC4 and PC6 with the pre-construction phase; CSFs C4 with the construction phase and CSFs O1 with operation phase compared to the other correlations between technology and CSFs in each BLC phase.

By cross-tabulation, we observed a narrow correlation between People (MacC3) and CSFs codes in the building life cycle phases represented in Figure 14. In turn, we noticed an expressive network between Process (MacC3) and CSFs codes represented by the links in Figure 15. The network analysis showed stronger correlations between CSFs D1, D2, D3, D4, and D12 with the design phase; CSFs PC2, PC4, PC6 with the pre-construction phase; CSFs C4 with construction phase compared to other correlations.

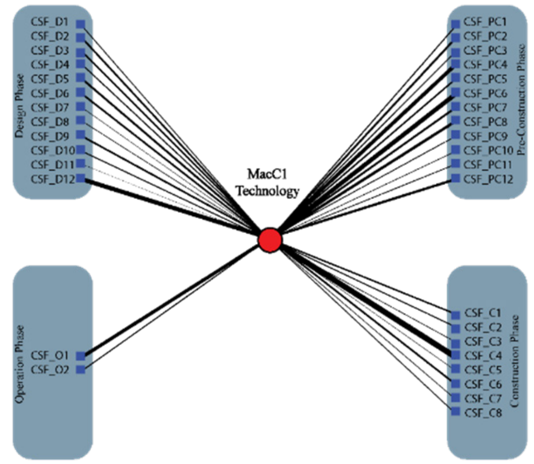

FIGURE 13: CORRELATION OF TECHNOLOGY BIM MACRO-CATEGORY WITH CSFS CODES (NOTE: APPLYING UCINET SOFTWARE)

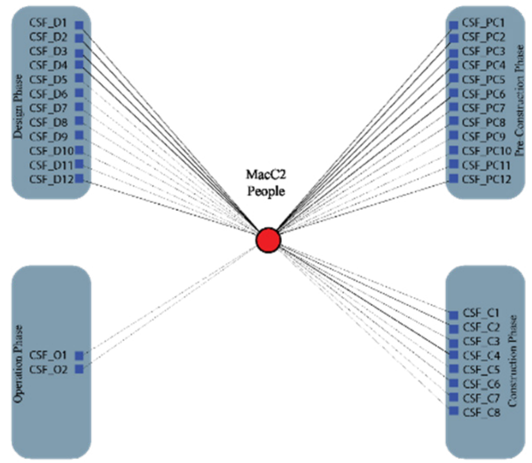

FIGURE 14: CORRELATION OF PEOPLE BIM MACRO-CATEGORY WITH CSFS CODES (NOTE: APPLYING UCINET SOFTWARE)

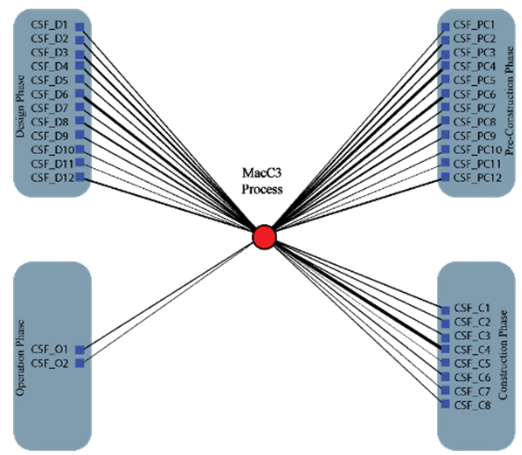

FIGURE 15: CORRELATION OF PROCESS BIM MACRO-CATEGORY WITH CSFS CODES (NOTE: APPLYING UCINET SOFTWARE)

4. DISCUSSION AND FUTURE RESEARCH AGENDA

By addressing Research question 1 (How has BIM been approached by Academia in the last decade?) we observed that BIM research has been more focused on topics related to technology than compared to processes and people in the last decade. We understood there is still a gap in the field to develop research exploring BIM not only as of the technology itself but as an integrated process in the building life cycle phases. We understand that BIM technology itself cannot solve construction problems commonly faced by the AEC industry.

There is a need for rethinking design and construction processes integrated with BIM solutions that rely on BIM-trained professionals. BIM adoption would require a change in the existing work practice (Porwal & Hewage, 2013). Thus, we consider Process and People as important macro-categories and as strong research streams to be developed in the BIM field.

Operational and management themes have been neglected compared to product themes in the field (Hosseini et al., 2018). For Barlish and Sullivan (2012), Organizational and project management functions can be affected by the implementation of BIM. By understanding there is a need to better integrate design and construction interface, we recognize the importance of developing new studies in the BIM research field allied to solutions of construction management methods, which can be able to diminish the lack of integration between design and construction phases in a more collaborative work environment.

We recognize there is a gap of knowledge between design and construction interface in the AEC industry. We hence considered the Pre-construction an important phase to be investigated and understood for reducing the fragmentation between design and construction phases. Thus, to better discuss this gap, we suggest a future research agenda presenting key findings and unsolved questions related to the Pre-construction phase by BIM macro-categories, as illustrated in Table 6. To discuss future research agendas, we selected papers from the content analysis database classified as BIM in the AEC industry (BIM research code) and Pre-construction CSFs code. We here present the main key findings and unsolved questions related to the Pre-construction phase codes categorized by BIM macro categories.

TABLE 6: FUTURE RESEARCH AGENDA PROPOSITION

BIM macro-categories	Key findings	Unsolved questions	Ref.
Technology MacC1	BIM-servers should provide technical features to support information sharing, communication media, process management, exploration space, privacy, and flexible system configuration. BIM-server technologies should not be limited to functional and operational requirements only because AEC projects are mostly multi-organizational and multi-disciplinary.	• The success of the BIM-server depends on its collective adoption by the stakeholders, who are expected to participate in the collaboration activities.	Singh et al., 2011)
	The choice of modeling tool should not be constrained by the type of object It is essential to use a structured system of IDs and layers to ensure the consistency of workflows. The success of the quantity takeoff process is highly dependent on parameters.	• The BIM model is still not able to fully meet all the users' needs • The approach to design has to change to adjust to these new tools, frameworks, and standards for structuring the use need to be developed and optimizing performance	(Monteiro & Martins, 2013)
Process MacC2	The benefits of the BIM framework involved: (1) Return metrics: change orders, RFIs, and schedule; and (2) Investment metrics: design costs and contractor costs.	• Large need for managerial effectiveness for BIM success • Organizational and project management functions affect the BIM implementation	(Barlish & Sullivan, 2012)
	Identified technical tool functional requirements and needs, and non-technical strategic issues for BIM adoption. There are varying levels of BIM adoption from country to country	• The need for guidance on where to start, how to work through the legal, procurement, and cultural challenges • BIM adoption would require a change in the existing work practice • Need for greater collaboration and communication across disciplines, data organization, and management	(Gu & London, 2010)
	Insights into how different types of institutional forces can be better manipulated to facilitate the diffusion of BIM in the construction industry	• The need to consider BIM adoption as a complex activity	(Cao et al., 2014)
	Performance measurement is a prerequisite for ensuring that PPPs are delivered by the project goals.	• There has been limited use of BIM within PPPs	(Love et al., 2015)
	Developed a framework to evaluate promising areas and to identify driving factors for practical BIM effectiveness	• Knowledge (of property level variable), reasoning (in ontology variable), and cost-effective approaches using structured BIM properties are the promising areas for advanced BIM	(Y. Jung & Joo, 2011)
	BIM technology adoption should be undertaken with a bottom-up approach rather than a top-down approach for a successful change in management and in dealing with the resistance to change.	• Successful BIM adoption needs an implementation strategy and professional guidelines are required for that.	(Arayici et al., 2011)
People MacC3	BIM is most often used in the early stages (design and pre-construction) with progressively less use in the later stages (construction and operation). 3D models are less significant compared to the increased collaboration, management aspects of the process, reduction of waste, and accuracy in the impacts of BIM. Lack of industry expertise and training provides an opportunity for education providers.	• Lack of expertise within the project team and external organizations • Need for educational and professional development for BIM training	(Eadie et al., 2013)
	Understanding how delivery decisions influence the integration and development of project teams and make building owners aware of how decisions affect the project performance	• Determine the effect of team integration and group cohesion on both sustainability and safety performance.	(Franz et al., 2017)
	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.	• Clear communication and collaboration between domain experts, consultants, and software developers are essential for the success of any advanced parametric modeling system for project development.	(G. Lee et al., 2006)

5. CONCLUSIONS AND LIMITATIONS

This study provided an overview of the BIM approach in Academia in the last decade. A total of 1,378 articles were collected from the Web of Science database. Bibliometrics mapped the main clusters of BIM research and the relevant authors in the field. We performed a co-citation network, co-occurrence of keywords, and citation network by sources to identify the current status and future trends of BIM in Academia.

Based on the first research question and the main research goal, we acknowledge that BIM is still a relevant topic in the field and its approach has been concentrated on understanding BIM as a technology compared to the process and people BIM macro-category. About the BIM approach in Academia, the findings showed Intelligence, BIM adoption in the AEC industry, Safety, and Sustainability as the research topics most studied in Academia in the last decade.

Concerning BIM macro-categories, Technology was the most representative BIM macro-category followed by Process and People. This denotes the majority of the articles analyzed were dedicated to the development of information technologies in the AEC industry. Therefore, the BIM approach has been mainly focused on topics related to interoperability; building performance; construction simulation; construction safety and code checking; energy, acoustic, and energy simulation in Academia.

The second research question and research goal allowed observing the relationship of BIM macro-categories with critical success factors in the building life cycle phases. We noticed that Process had a stronger correlation with CSFs compared to Technology and People BIM macro categories. Particularly, we noticed 9 out of 34 CSFs had stronger link correlations with the Process BIM macro-category, five of which were related to the design phase, three with the pre-construction phase, and one with the construction phase.

In conclusion, after crossing and analyzing the data from bibliometrics, content analysis, and cross-tabulation, we suggest the importance of developing studies focused on the enhancement of BIM research related to Process and People BIM macro-categories, once the Technology BIM macro-category has been more studied in the field. In addition, data analysis also showed the relevance of studying design and construction interface with the evidence that the most significant subphases in the building life cycle were Analysis, detailing, coordination, and specification which is the last subphase of the design phase and, Construction planning and construction detailing as the first subphase of the construction phase.

Finally, this study has some methodological limitations: First, the data was collected only from the Web of Science database. Second, data has limitations regarding the adoption of search strategy, search strings, and logical operators. Third, the data analysis can have some bias based on our authors 'knowledge and perception regarding the topic'. As future works, we suggest a broader investigation with other research databases adopting the codes created in this study, besides an analysis of critical success factors for BIM in the building life cycle subphases to understand the potential research gaps between those subphases.

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REFERENCES

Akbarnezhad, A., Ong, K. C. G., & Chandra, L. R. (2014). Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in construction, 37*, 131-144. https://doi.org/10.1016/j.autcon.2013.10.017

Anil, E. B., Tang, P., Akinci, B., & Huber, D. (2013). Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data. *Automation in construction, 35*, 507-516. https://doi.org/10.1016/j.autcon.2013.06.003

Antwi-Afari, M., Li, H., Pärn, E., & Edwards, D. J. (2018). Critical success factors for implementing building information modelling (BIM): A longitudinal review. *Automation in construction, 91*, 100-110. https://doi.org/10.1016/j.autcon.2018.03.010

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., & O'Reilly, K. (2011). Technology adoption in the BIM implementation for lean architectural practice. *Automation in construction, 20*(2), 189-195. https://doi.org/10.1016/j.autcon.2010.09.016

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of informetrics, 11*(4), 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Asl, M. R., Zarrinmehr, S., Bergin, M., & Yan, W. (2015). BPOpt: A framework for BIM-based performance optimization. *Energy and Buildings, 108*, 401-412. https://doi.org/10.1016/j.enbuild.2015.09.011

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering, 11*(3), 241-252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Azhar, S., Carlton, W. A., Olsen, D., & Ahmad, I. (2011). Building information modeling for sustainable design and LEED® rating analysis. *Automation in Construction, 20*(2), 217-224. https://doi.org/10.1016/j.autcon.2010.09.019

Barlish, K., & Sullivan, K. (2012). How to measure the benefits of BIM—A case study approach. *Automation in construction, 24*, 149-159. https://doi.org/10.1016/j.autcon.2012.02.008

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment, 60*, 81-92. https://doi.org/10.1016/j.buildenv.2012.11.009

Becerik-Gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application Areas and Data Requirements for BIM-Enabled Facilities Management. *Journal of Construction Engineering and Management, 138*(3), 431-442. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000433

Borgatti, S. P., Everett, M. G., & Freeman, L. C. (2002). Ucinet for Windows: Software for social network analysis. *Harvard, MA: analytic technologies, 6*, 12-15.

Borrmann, A., Kolbe, T. H., Donaubauer, A., Steuer, H., Jubierre, J. R., & Flurl, M. (2015). Multi-scale geometric-semantic modeling of shield tunnels for GIS and BIM applications. *Computer-Aided Civil and Infrastructure Engineering, 30*(4), 263-281. https://doi.org/10.1111/mice.12090

Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., & Haas, R. (2015). The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. *Automation in Construction, 49*, 201-213. https://doi.org/10.1016/j.autcon.2014.05.014

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. *Automation in Construction, 71*, 139-152. https://doi.org/10.1016/j.autcon.2016.08.019

Bruno, S., De Fino, M., & Fatiguso, F. (2018). Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management. *Automation in Construction, 86*, 256-276. https://doi.org/10.1016/j.autcon.2017.11.009

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International journal of project management, 31*(7), 971-980. https://doi.org/10.1016/j.ijproman.2012.12.001

Bynum, P., Issa, R. R., & Olbina, S. (2013). Building information modeling in support of sustainable design and construction. *Journal of construction engineering and management, 139*(1), 24-34. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560

Cao, D., Li, H., & Wang, G. (2014). Impacts of isomorphic pressures on BIM adoption in construction projects. *Journal of construction engineering and management, 140*(12), 1-9. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000903

Cao, D., Li, H., Wang, G., & Huang, T. (2017). Identifying and contextualising the motivations for BIM implementation in construction projects: An empirical study in China. *International journal of project management, 35*(4), 658-669. https://doi.org/10.1016/j.ijproman.2016.02.002

Cao, D., Wang, G., Li, H., Skitmore, M., Huang, T., & Zhang, W. (2015). Practices and effectiveness of building information modelling in construction projects in China. *Automation in construction, 49*, 113-122. https://doi.org/10.1016/j.autcon.2014.10.014

Carvalho, M. M., Fleury, A., & Lopes, A. P. (2013). An overview of the literature on technology roadmapping (TRM): Contributions and trends. *Technological Forecasting and Social Change, 80*(7), 1418-1437. https://doi.org/10.1016/j.techfore.2012.11.008

Chen, L., & Luo, H. (2014). A BIM-based construction quality management model and its applications. *Automation in construction, 46*, 64-73. https://doi.org/10.1016/j.autcon.2014.05.009

Chien, K.-F., Wu, Z.-H., & Huang, S.-C. (2014). Identifying and assessing critical risk factors for BIM projects: Empirical study. *Automation in construction, 45*, 1-15. https://doi.org/10.1016/j.autcon.2014.04.012

Dave, B., Kubler, S., Främling, K., & Koskela, L. (2016). Opportunities for enhanced lean construction management using Internet of Things standards. *Automation in construction, 61*, 86-97. https://doi.org/10.1016/j.autcon.2015.10.009

Davies, R., & Harty, C. (2013). Implementing 'Site BIM': A case study of ICT innovation on a large hospital project. *Automation in construction, 30*, 15-24. https://doi.org/10.1016/j.autcon.2012.11.024

Deng, Y., Cheng, J. C. P., & Anumba, C. (2016). Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. *Automation in Construction, 67*, 1-21. https://doi.org/10.1016/j.autcon.2016.03.006

Ding, L., Zhou, Y., & Akinci, B. (2014). Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD. *Automation in construction, 46*, 82-93. https://doi.org/10.1016/j.autcon.2014.04.009

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment, 123*, 243-260. https://doi.org/10.1016/j.buildenv.2017.07.007

Dong, B., O'Neill, Z., & Li, Z. (2014). A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics. *Automation in Construction, 44*, 197-211. https://doi.org/10.1016/j.autcon.2014.04.007

Dossick, C. S., & Neff, G. (2010). Organizational divisions in BIM-enabled commercial construction. *Journal of construction engineering and management, 136*(4), 459-467. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000109

Du, J., Zou, Z., Shi, Y., & Zhao, D. (2018). Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Automation in Construction, 85*, 51-64. https://doi.org/10.1016/j.autcon.2017.10.009

Duriau, V. J., Reger, R. K., & Pfarrer, M. D. (2007). A content analysis of the content analysis literature in organization studies: Research themes, data sources, and methodological refinements. *Organizational research methods, 10*(1), 5-34. https://doi.org/10.1177%2F1094428106289252

Eadie, R., Browne, M., Odeyinka, H., McKeown, C., & McNiff, S. (2013). BIM implementation throughout the UK construction project lifecycle: An analysis. *Automation in construction, 36*, 145-151. https://doi.org/10.1016/j.autcon.2013.09.001

Eastman, C., Lee, J.-m., Jeong, Y.-s., & Lee, J.-k. (2009). Automatic rule-based checking of building designs. *Automation in Construction, 18*(8), 1011-1033. https://doi.org/10.1016/j.autcon.2009.07.002

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Wiley. https://books.google.com.pk/books?id=IioygN0nYzMC

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Wiley. https://books.google.com.pk/books?id=-GjrBgAAQBAJ

El-Diraby, T., Krijnen, T., & Papagelis, M. (2017). BIM-based collaborative design and socio-technical analytics of green buildings. *Automation in Construction, 82*, 59-74. https://doi.org/10.1016/j.autcon.2017.06.004

Fang, W., Ding, L., Luo, H., & Love, P. E. (2018). Falls from heights: A computer vision-based approach for safety harness detection. *Automation in Construction, 91*, 53-61. https://doi.org/10.1016/j.autcon.2018.02.018

Fang, Y., Cho, Y. K., Zhang, S., & Perez, E. (2016). Case study of BIM and cloud–enabled real-time RFID indoor localization for construction management applications. *Journal of Construction Engineering and Management, 142*(7), 1-12. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001125

Franz, B., Leicht, R., Molenaar, K., & Messner, J. (2017). Impact of team integration and group cohesion on project delivery performance. *Journal of construction engineering and management, 143*(1), 1-12. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001219

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M., & Lowry, C. (2017). BIM application to building energy performance visualisation and management: Challenges and potential. *Energy and Buildings, 144*, 218-228. https://doi.org/10.1016/j.enbuild.2017.03.032

Giannantonio, C. M. (2010). Book review: Krippendorff, K.(2004). Content analysis: an introduction to its methodology . Thousand oaks, CA: sage. *Organizational Research Methods, 13*(2), 392-394. https://doi.org/10.1177%2F1094428108324513

Göçer, Ö., Hua, Y., & Göçer, K. (2015). Completing the missing link in building design process: Enhancing post-occupancy evaluation method for effective feedback for building performance. *Building and Environment, 89*, 14-27. https://doi.org/10.1016/j.buildenv.2015.02.011

Goedert, J. D., & Meadati, P. (2008). Integrating construction process documentation into building information modeling. *Journal of construction engineering and management, 134*(7), 509-516. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:7(509)

Grilo, A., & Jardim-Goncalves, R. (2010). Value proposition on interoperability of BIM and collaborative working environments. *Automation in construction, 19*(5), 522-530. https://doi.org/10.1016/j.autcon.2009.11.003

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in construction, 19*(8), 988-999. https://doi.org/10.1016/j.autcon.2010.09.002

Guo, H., Yu, Y., & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction, 73*, 135-144. https://doi.org/10.1016/j.autcon.2016.10.004

Habibi, S. (2017). The promise of BIM for improving building performance. *Energy and Buildings, 153*, 525-548. https://doi.org/10.1016/j.enbuild.2017.08.009

Ham, Y., & Golparvar-Fard, M. (2015). Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in Construction, 49*, 214-224. https://doi.org/10.1016/j.autcon.2014.07.009

Han, K. K., & Golparvar-Fard, M. (2015). Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs. *Automation in construction, 53*, 44-57. https://doi.org/10.1016/j.autcon.2015.02.007

Han, K. K., & Golparvar-Fard, M. (2017). Potential of big visual data and building information modeling for construction performance analytics: An exploratory study. *Automation in Construction, 73*, 184-198. https://doi.org/10.1016/j.autcon.2016.11.004

Hartmann, T., Van Meerveld, H., Vossebeld, N., & Adriaanse, A. (2012). Aligning building information model tools and construction management methods. *Automation in construction, 22*, 605-613. https://doi.org/10.1016/j.autcon.2011.12.011

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International journal of project management, 35*(4), 670-685. https://doi.org/10.1016/j.ijproman.2016.08.001

Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., & Chileshe, N. (2018). Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in Construction, 87*, 235-247. https://doi.org/10.1016/j.autcon.2017.12.002

Iddon, C. R., & Firth, S. K. (2013). Embodied and operational energy for new-build housing: A case study of construction methods in the UK. *Energy and Buildings, 67*, 479-488. https://doi.org/10.1016/j.enbuild.2013.08.041

Ilhan, B., & Yaman, H. (2016). Green building assessment tool (GBAT) for integrated BIM-based design decisions. *Automation in Construction, 70*, 26-37. https://doi.org/10.1016/j.autcon.2016.05.001

Irizarry, J., Karan, E. P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in construction, 31*, 241-254. https://doi.org/10.1016/j.autcon.2012.12.005

Jalaei, F., & Jrade, A. (2015). Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society, 18*, 95-107. https://doi.org/10.1016/j.scs.2015.06.007

Jung, J., Hong, S., Jeong, S., Kim, S., Cho, H., Hong, S., & Heo, J. (2014). Productive modeling for development of as-built BIM of existing indoor structures. *Automation in Construction, 42*, 68-77. https://doi.org/10.1016/j.autcon.2014.02.021

Jung, Y., & Joo, M. (2011). Building information modelling (BIM) framework for practical implementation. *Automation in construction, 20*(2), 126-133. https://doi.org/10.1016/j.autcon.2010.09.010

Karan, E. P., & Irizarry, J. (2015). Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services. *Automation in Construction, 53*, 1-12. https://doi.org/10.1016/j.autcon.2015.02.012

Kim, C., Son, H., & Kim, C. (2013). Automated construction progress measurement using a 4D building information model and 3D data. *Automation in construction, 31*, 75-82. https://doi.org/10.1016/j.autcon.2012.11.041

Kim, H., Anderson, K., Lee, S., & Hildreth, J. (2013). Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Automation in Construction, 35*, 285-295. https://doi.org/10.1016/j.autcon.2013.05.020

Kim, J. B., Jeong, W., Clayton, M. J., Haberl, J. S., & Yan, W. (2015). Developing a physical BIM library for building thermal energy simulation. *Automation in construction, 50*, 16-28. https://doi.org/10.1016/j.autcon.2014.10.011

Kim, K., Cho, Y., & Zhang, S. (2016). Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM. *Automation in Construction, 70*, 128-142. https://doi.org/10.1016/j.autcon.2016.06.012

Kim, M.-K., Cheng, J. C., Sohn, H., & Chang, C.-C. (2015). A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning. *Automation in Construction, 49*, 225-238. https://doi.org/10.1016/j.autcon.2014.07.010

Kim, M.-K., Wang, Q., Park, J.-W., Cheng, J. C., Sohn, H., & Chang, C.-C. (2016). Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. *Automation in Construction, 72*, 102-114. https://doi.org/10.1016/j.autcon.2016.08.035

Kitchenham, B. (2004). Procedures for performing systematic reviews. *Keele, UK, Keele University, 33*(2004), 1-26. https://www.researchgate.net/publication/228756057

Klein, L., Li, N., & Becerik-Gerber, B. (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in construction, 21*, 161-171. https://doi.org/10.1016/j.autcon.2011.05.023

Kumar, S. S., & Cheng, J. C. (2015). A BIM-based automated site layout planning framework for congested construction sites. *Automation in Construction, 59*, 24-37. https://doi.org/10.1016/j.autcon.2015.07.008

Lee, G., Sacks, R., & Eastman, C. M. (2006). Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in construction, 15*(6), 758-776. https://doi.org/10.1016/j.autcon.2005.09.009

Lee, S.-K., Kim, K.-R., & Yu, J.-H. (2014). BIM and ontology-based approach for building cost estimation. *Automation in Construction, 41*, 96-105. https://doi.org/10.1016/j.autcon.2013.10.020

Li, C. Z., Xue, F., Li, X., Hong, J., & Shen, G. Q. (2018). An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Automation in construction, 89*, 146-161. https://doi.org/10.1016/j.autcon.2018.01.001

Li, N., Becerik-Gerber, B., Krishnamachari, B., & Soibelman, L. (2014). A BIM centered indoor localization algorithm to support building fire emergency response operations. *Automation in Construction, 42*, 78-89. https://doi.org/10.1016/j.autcon.2014.02.019

Li, X., Wu, P., Shen, G. Q., Wang, X., & Teng, Y. (2017). Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach. *Automation in Construction, 84*, 195-206. https://doi.org/10.1016/j.autcon.2017.09.011

Littell, J. H., Corcoran, J., & Pillai, V. (2008). *Systematic Reviews and Meta-Analysis*. Oxford University Press, USA. https://books.google.com.pk/books?id=UpsRDAAAQBAJ

Liu, H., Al-Hussein, M., & Lu, M. (2015). BIM-based integrated approach for detailed construction scheduling under resource constraints. *Automation in Construction, 53*, 29-43. https://doi.org/10.1016/j.autcon.2015.03.008

Liu, S., Meng, X., & Tam, C. (2015). Building information modeling based building design optimization for sustainability. *Energy and Buildings, 105*, 139-153. https://doi.org/10.1016/j.enbuild.2015.06.037

Liu, Y., Van Nederveen, S., & Hertogh, M. (2017). Understanding effects of BIM on collaborative design and construction: An empirical study in China. *International journal of project management, 35*(4), 686-698. https://doi.org/10.1016/j.ijproman.2016.06.007

Love, P. E., Liu, J., Matthews, J., Sing, C.-P., & Smith, J. (2015). Future proofing PPPs: life-cycle performance measurement and building information modelling. *Automation in Construction, 56*, 26-35. https://doi.org/10.1016/j.autcon.2015.04.008

Love, P. E., Simpson, I., Hill, A., & Standing, C. (2013). From justification to evaluation: Building information modeling for asset owners. *Automation in construction, 35*, 208-216. https://doi.org/10.1016/j.autcon.2013.05.008

Lu, Y., Wu, Z., Chang, R., & Li, Y. (2017). Building Information Modeling (BIM) for green buildings: A critical review and future directions. *Automation in Construction, 83*, 134-148. https://doi.org/10.1016/j.autcon.2017.08.024

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in construction, 43*, 84-91. https://doi.org/10.1016/j.autcon.2014.03.009

Monteiro, A., & Martins, J. P. (2013). A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Automation in construction, 35*, 238-253. https://doi.org/10.1016/j.autcon.2013.05.005

Motamedi, A., Hammad, A., & Asen, Y. (2014). Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management. *Automation in construction, 43*, 73-83. https://doi.org/10.1016/j.autcon.2014.03.012

Negendahl, K. (2015). Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction, 54*, 39-53. https://doi.org/10.1016/j.autcon.2015.03.002

Park, C.-S., & Kim, H.-J. (2013). A framework for construction safety management and visualization system. *Automation in Construction, 33*, 95-103. https://doi.org/10.1016/j.autcon.2012.09.012

Park, C.-S., Lee, D.-Y., Kwon, O.-S., & Wang, X. (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Automation in Construction, 33*, 61-71. https://doi.org/10.1016/j.autcon.2012.09.010

Park, J., & Cai, H. (2017). WBS-based dynamic multi-dimensional BIM database for total construction as-built documentation. *Automation in Construction, 77*, 15-23. https://doi.org/10.1016/j.autcon.2017.01.021

Park, J., Kim, K., & Cho, Y. K. (2017). Framework of automated construction-safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors. *Journal of Construction Engineering and Management, 143*(2), 1-12. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001223

Pärn, E. A., Edwards, D. J., & Sing, M. C. (2017). The building information modelling trajectory in facilities management: A review. *Automation in construction, 75*, 45-55. https://doi.org/10.1016/j.autcon.2016.12.003

Patacas, J., Dawood, N., & Kassem, M. (2020). BIM for facilities management: A framework and a common data environment using open standards. *Automation in Construction, 120*, 103366. https://doi.org/10.1016/j.autcon.2020.103366

Paul, J., & Criado, A. R. (2020). The art of writing literature review: What do we know and what do we need to know? *International Business Review, 29*(4), 101717. https://doi.

org/10.1016/j.ibusrev.2020.101717
Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., & Van Campenhout, J. (2011). A semantic rule checking environment for building performance checking. *Automation in Construction, 20*(5), 506-518. https://doi.org/10.1016/j.autcon.2010.11.017
Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction, 73*, 145-165. https://doi.org/10.1016/j.autcon.2016.10.003
Pinheiro, S., Wimmer, R., O'Donnell, J., Muhic, S., Bazjanac, V., Maile, T., . . . van Treeck, C. (2018). MVD based information exchange between BIM and building energy performance simulation. *Automation in Construction, 90*, 91-103. https://doi.org/10.1016/j.autcon.2018.02.009
Pishdad-Bozorgi, P., Gao, X., Eastman, C., & Self, A. P. (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation in Construction, 87*, 22-38. https://doi.org/10.1016/j.autcon.2017.12.004
Porwal, A., & Hewage, K. N. (2013). Building Information Modeling (BIM) partnering framework for public construction projects. *Automation in construction, 31*, 204-214. https://doi.org/10.1016/j.autcon.2012.12.004
Ramos-Rodríguez, A. R., & Ruíz-Navarro, J. (2004). Changes in the intellectual structure of strategic management research: A bibliometric study of the Strategic Management Journal, 1980–2000. *Strategic management journal, 25*(10), 981-1004. https://doi.org/10.1002/smj.397
Redmond, A., Hore, A., Alshawi, M., & West, R. (2012). Exploring how information exchanges can be enhanced through Cloud BIM. *Automation in construction, 24*, 175-183. https://doi.org/10.1016/j.autcon.2012.02.003
Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of lean and building information modeling in construction. *Journal of construction engineering and management, 136*(9), 968-980. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203
Sacks, R., Ma, L., Yosef, R., Borrmann, A., Daum, S., & Kattel, U. (2017). Semantic enrichment for building information modeling: Procedure for compiling inference rules and operators for complex geometry. *Journal of Computing in Civil Engineering, 31*(6), 1-12. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000705
Sacks, R., Radosavljevic, M., & Barak, R. (2010). Requirements for building information modeling based lean production management systems for construction. *Automation in construction, 19*(5), 641-655. https://doi.org/10.1016/j.autcon.2010.02.010
Santos, R., Costa, A. A., & Grilo, A. (2017). Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Automation in Construction, 80*, 118-136. https://doi.org/10.1016/j.autcon.2017.03.005
Schlueter, A., & Thesseling, F. (2009). Building information model based energy/exergy performance assessment in early design stages. *Automation in construction, 18*(2), 153-163. https://doi.org/10.1016/j.autcon.2008.07.003
Schöggl, J.-P., Stumpf, L., & Baumgartner, R. J. (2020). The narrative of sustainability and circular economy-A longitudinal review of two decades of research. *Resources, Conservation and Recycling, 163*, 105073. https://doi.org/10.1016/j.resconrec.2020.105073
Shadram, F., Johansson, T. D., Lu, W., Schade, J., & Olofsson, T. (2016). An integrated BIM-based framework for minimizing embodied energy during building design. *Energy and Buildings, 128*, 592-604. https://doi.org/10.1016/j.enbuild.2016.07.007
Singh, V., Gu, N., & Wang, X. (2011). A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in construction, 20*(2), 134-144. https://doi.org/10.1016/j.autcon.2010.09.011
Solihin, W., & Eastman, C. (2015). Classification of rules for automated BIM rule checking development. *Automation in construction, 53*, 69-82. https://doi.org/10.1016/j.autcon.2015.03.003
Son, H., Lee, S., & Kim, C. (2015). What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions. *Automation in construction, 49*, 92-99. https://doi.org/10.1016/j.autcon.2014.10.012
Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2017). Critical review of bim-based LCA method to buildings. *Energy and Buildings, 136*, 110-120. https://doi.org/10.1016/j.enbuild.2016.12.009
Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in construction, 18*(3), 357-375. https://doi.org/10.1016/j.autcon.2008.10.003
Succar, B., & Kassem, M. (2015). Macro-BIM adoption: Conceptual structures. *Automation in Construction, 57*, 64-79. https://doi.org/10.1016/j.autcon.2015.04.018
Succar, B., Sher, W., & Williams, A. (2013). An integrated approach to BIM competency assessment, acquisition and application. *Automation in Construction, 35*, 174-189. https://doi.org/10.1016/j.autcon.2013.05.016
Takey, S. M., & Carvalho, M. M. (2016). Fuzzy front end of systemic innovations: A conceptual framework based on a systematic literature review. *Technological Forecasting and Social Change, 111*, 97-109. https://doi.org/10.1016/j.techfore.2016.06.011
Tang, P., Huber, D., Akinci, B., Lipman, R., & Lytle, A. (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in construction, 19*(7), 829-843. https://doi.org/10.1016/j.autcon.2010.06.007
Vanlande, R., Nicolle, C., & Cruz, C. (2008). IFC and building lifecycle management. *Automation in construction, 18*(1), 70-78. https://doi.org/10.1016/j.autcon.2008.05.001
Victor, L. (2008). Systematic reviewing. *Social research update, 54*(1), 1-4. https://www.academia.edu/download/43891132/Systematic_Reviewing.pdf
Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in construction, 38*, 109-127. https://doi.org/10.1016/j.autcon.2013.10.023
Wang, C., Cho, Y. K., & Kim, C. (2015). Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. *Automation in Construction, 56*, 1-13. https://doi.org/10.1016/j.autcon.2015.04.001
Wang, H., & Zhai, Z. J. (2016). Advances in building simulation and computational techniques: A review between 1987 and 2014. *Energy and Buildings, 128*, 319-335. https://doi.org/10.1016/j.enbuild.2016.06.080
Wang, X., Love, P. E., Kim, M. J., Park, C.-S., Sing, C.-P., & Hou, L. (2013). A conceptual framework for integrating building information modeling with augmented reality. *Automation in construction, 34*, 37-44. https://doi.org/10.1016/j.autcon.2012.10.012
Wang, X., Truijens, M., Hou, L., Wang, Y., & Zhou, Y. (2014). Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry. *Automation in Construction, 40*, 96-105. https://doi.org/10.1016/j.autcon.2013.12.003
Weber, R. P. (1990). *Basic Content Analysis*. Sage. https://books.google.com.pk/books?id=nLhZm7Lw2FwC
Wetzel, E. M., & Thabet, W. Y. (2015). The use of a BIM-based framework to support safe facility management processes. *Automation in Construction, 60*, 12-24. https://doi.org/10.1016/j.autcon.2015.09.004
Wong, J. K. W., & Zhou, J. (2015). Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in construction, 57*, 156-165. https://doi.org/10.1016/j.autcon.2015.06.003
Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction, 68*, 21-31. https://doi.org/10.1016/j.autcon.2016.04.005
Xiong, X., Adan, A., Akinci, B., & Huber, D. (2013). Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in construction, 31*, 325-337. https://doi.org/10.1016/j.autcon.2012.10.006
Yalcinkaya, M., & Singh, V. (2015). Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis. *Automation in Construction, 59*, 68-80. https://doi.org/10.1016/j.autcon.2015.07.012
Zhang, J., & Hu, Z. (2011). BIM-and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Automation in construction, 20*(2), 155-166. https://doi.org/10.1016/j.autcon.2010.09.013
Zhang, S., Boukamp, F., & Teizer, J. (2015). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction, 52*, 29-41. https://doi.org/10.1016/j.autcon.2015.02.005
Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., & Venugopal, M. (2013). Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in construction, 29*, 183-195. https://doi.org/10.1016/j.autcon.2012.05.006
Zhang, S., Teizer, J., Pradhananga, N., & Eastman, C. M. (2015). Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning. *Automation in Construction, 60*, 74-86. https://doi.org/10.1016/j.autcon.2015.09.009
Zhao, X. (2017). A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction, 80*, 37-47. https://doi.org/10.1016/j.autcon.2017.04.002
Zhong, R. Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Huang, G. Q. (2017). Prefabricated construction enabled by the Internet-of-Things. *Automation in Construction, 76*, 59-70. https://doi.org/10.1016/j.autcon.2017.01.006
Zhou, W., Whyte, J., & Sacks, R. (2012). Construction safety and digital design: A review. *Automation in Construction, 22*, 102-111. https://doi.org/10.1016/j.autcon.2011.07.005

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