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EVOLUTION IN THE INTELLECTUAL STRUCTURE OF BIM RESEARCH: A BIBLIOMETRIC ANALYSIS

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Abstract. Building Information Modelling (BIM) processes have continued to gain relevance in the Architectural, Engineering, and Construction (AEC) industry with more resources directed toward it. This study conducts a bibliometric analysis of 445 BIM articles to investigate and understand the pattern of BIM research which include defining BIM research categories, evaluating the project sectors that are influenced by BIM, and tracking the funding structure of BIM research. A network map that displays a visualization of the structure of BIM literature by research origin, funding structure and geographical scope was designed. None of the previous reviews of literature analyzed the BIM articles' corpus to such level and depth. The findings revealed research categories such as construction and project management and BIM learning, adoption & practice as the core research areas in BIM and highlighted trending research themes in BIM research. Authors based in Asia and Europe received more research grants than their counterparts in other regions; likewise, two-third of the articles was authored by academics in the United States, Korea, and the United Kingdom. The study provides its readers with relevant research areas that require considerations, and the discussion of selected research areas provides an extensive understanding of salient BIM fields.

Keywords: Building Information Modelling (BIM), bibliometric analysis, funding structure, project sectors, research areas, BIM software.

Introduction

Building Information Modelling (BIM) is currently receiving worldwide recognition in the AEC industry due to its ability to store and also ease the use and reuse of project data across the project development phases; while also preventing unnecessary replication of project or design tasks (Kovacic *et al.* 2015; Kim *et al.* 2013; Lee, Yu 2016; Sun, Wang 2015). However, BIM is a revolving and innovative digital technology (Mahalingam *et al.* 2015; Malekitabar *et al.* 2016; Succar, Kassem 2015); with recent applications in areas such as sustainability (Ajayi *et al.* 2015; Liu *et al.* 2015a) and facility management (Motamedi *et al.* 2013); despite the fragmented nature of the construction industry.

Meanwhile, BIM has started to receive more attention in the academic community with several research papers on BIM. It include articles on the development of BIM curriculum for university undergraduate students. Related works on BIM curriculum development including literature such as "*course development and collaborative teaching*" (see Ahn *et al.* 2013; Becerik-Gerber, Kensek 2010; Becerik-Gerber *et al.* 2012a; Kim 2012; Sacks, Barak 2010; Wang, Leite 2014; Wu, Issa 2014). It also includes "*evaluating BIM curriculum vis-à-vis industrial needs*" (Aibinu, Venkatesh 2014; Solnosky *et al.* 2014) and "*in-class experimentation with BIM tools*" (Lewis *et al.* 2015; Nassar 2012) among many other related topics.

BIM per Eastman *et al.* (2008) is "a new approach to design, construction, and facilities management, in which a digital representation of the building process [is used] to facilitate the exchange and interoperability of information in digital format". Gilkinson *et al.* (2015) regarded it as both constituting a process and technology. It is an innovative solution with much to be explored; they further stressed that since it ensured a "coordinated integrated process"; it is a useful tool for all project stakeholders as they could found it fit and suitable for their jobs due to its diverse nature (Olawumi, Ayegun 2016), and the collaborative outlook of the construction industry (Olatunji *et al.* 2016a, 2016b), despite the increasing complexity of construction projects (Olatunji *et al.* 2017a). Olatunji *et al.* (2017b) listed one of the benefits of BIM as an increase

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in return on investment (ROI) for clients; and to "*facilitate the ease of dissemination of information*" and this, in turn, helps to secure project success (Olawumi 2016; Olawumi *et al.* 2016). Also, related technological tools such as augmented reality (AR) system and Geographic Information System (GIS) have also been integrated into the BIM process to facilitate the visualization of the construction process.

1. Knowledge gap and research objectives and value

Previous studies on reviews of BIM literature have focused on specific research areas or themes such as facility management (Becerik-Gerber *et al.*2012b; Kang, Hong 2015; Wetzel, Thabet 2015), environmental sustainability (Wong, Zhou 2015). Studies have outlined the current practices and future directions via various research approaches such as surveys, critical literature reviews, and interviews (Azhar 2011; Gu, London 2010; Volk *et al.* 2014). More so, researchers have carried out reviews and analyses on BIM which include contractors' blueprint to adopt BIM (Ahn *et al.* 2016); e-tendering process model (Ajam *et al.* 2010); waste management (Ajayi *et al.* 2015; Akinade *et al.* 2015); education and knowledge (Ahn *et al.* 2013; Alci, Sampaio 2015). Others include: social network simulation, cloud-BIM and technology adoptions (Al Hattab *et al.* 2015; Alreshidi *et al.* 2016; Arayici *et al.* 2011; Becerik-Gerber *et al.* 2012a; Becerik-Gerber, Kensek 2010; Chen, Hou 2014; Choi, Kim 2015; Davies, Harty 2013; Du *et al.* 2014).

Extant studies also exist on BIM-GIS integration (Bansal 2011; Borrmann *et al.* 2015; Deng *et al.* 2016) and sustainability (Bynum *et al.* 2013; Henry *et al.* 2015; Inyim *et al.* 2015). However, in recent years (2015–2017) there have been literature reviews (see Table 1 and Table 2) on BIM research field such as Yalcinkaya and Singh (2015), who reviewed BIM literature to deduce twelve (12) BIM core research areas and ninety (90) factor labels using Latent Semantic Analysis (LSA) described as a "natural language processing technique"; which was used to analyze the abstracts of the journal articles. Meanwhile, Zhao (2017) used a computer software "Citespace" to examine citation records downloaded from the Web of Science database to identify authors with the most citations and co-citations and the "hot topics" in BIM research areas with the most citations. More so, Santos *et al.* (2017) review of the extant literature focused on identifying research areas with the most citations and the most cited authors. Accordingly, he also proposed nine (9) research areas in BIM field. Table 1 and Table 2 identifies and summarize what is new in this current study and compares it with previous published reviews of BIM literature.

Moreover, previous BIM reviews focused mostly on authors and journals' citations analyses, this study attempts to bridge the gap in the reviews of extant literature and add value to BIM knowledge area. This study proposes the following objectives: (1) to carry out an holistic review of BIM journal articles (as against abstracts' review by Yalcinkaya and Singh (2015) and citations records by Zhao (2017)); (2) to define the subfields that constitute the intellectual structure of BIM research fields (core research categories and areas); (3) to identify funding (grants) structure for BIM research based on country (research origin) analysis and research category analysis; (4) to identify and establish the network of BIM publication by research origin and geographical scope; (5) to identify the salient research methodology employed in past BIM studies; (6) to identify relevant BIM software, data schema, and project areas for BIM application; and (7) to classify BIM publications based on project sectors they are applied to (such as energy, transportation, etc.).

Meanwhile, throughout the bibliometric analysis and the literature reviews, the study would adopt a more systematical and analytical approach in achieving the seven (7) objectives of this study. A wide range of publication will be analyzed across several journal publication houses. The next section focuses on a discussion of the research methodology applied (bibliometric analysis) and the literature search strategy. Other sections focus on (i) the findings and discussion of the results of the bibliometric analysis; (ii) discussion on the proposed core BIM research categories and areas; (iii) the research implications; (iv) research limitations; and (v) the conclusion and future directions.

2. Research methodology

The study adopted a bibliometric analysis technique to achieve the predefined research objectives of which is to articulate the distinct set of the main research categories in BIM's research to gain a better perspective and identify critical areas in which more research efforts is still been required. Per Marsilio *et al.* (2011) bibliometric research approach is an "*attempt(s) to quantify and address the intellectual structure of a research field starting from the mathematical and statistical analysis of patterns that appear in the publication and use of documents*". Meanwhile, this analysis technique has been utilized in some research publications both in the science and management research fields (see Neto *et al.* 2016; Marsilio *et al.* 2011; Ramos-Rodríguez, Ruíz-Navarro 2004).

This research aims to bridge the gap in the BIM literature by applying the bibliometric technique to a corpus of published articles relevant to this disciplinary field towards achieving the predefined objectives as stated in the previous section. The research design for this study is as outlined in Figure 1.

2.1. Literature search strategy

In commencing the bibliometric analysis, a decision as to which scientific repository to use was made; there are several academic digital databases, but the three most commonly utilized for scientific inquiries include Google Scholar, ISI Web of Science and Scopus. Although there is no clear difference in Scopus and Web of Science databases as it pertains to science-based

Table 1. Summary of recent BIM literature reviews

Paper	Number of journals analyzed	Number of papers analyzed	Period of analysis	Proposed research categories (*research areas*)	Research areas	Type of literature review	Scope/Focus of analysis
Wong and Zhou (2015)	9	84	2004–2014	4 (none)	– Green-BIM – Sustainability	No bibliometric	Each journal paper' sections
Yalcinkaya and Singh (2015)	Only Top 20 journal listed	– 525 journal articles – 450 conference papers	2004–2014	12 (90)	BIM	Latent Semantic Analysis (LSA)	Abstracts
Zhao (2017)	–	614	2005–2016	–	BIM	Scientometric review	Citation records only – Co-author analysis – Co-word analysis – Co-citation analysis – Co-occurring keywords
Santos *et al.* (2017)	49	381	2005–2015	9	BIM	Content analysis	Each journal paper' sections
Current study	62	445	2006–2016	10 (107)	– BIM – Review of sustainability studies	Bibliometric analysis	Each journal paper' sections

Table 2. Comparison between previous BIM literature reviews' findings and the current study

Paper	Database used	Contribution to existing knowledge
Wong and Zhou (2015)	Scopus	– Provided a summary of research focus of green-BIM publications – Identified the low utilization of BIM in facility management phase – Proposed a 'one-stop-shop' BIM for environmental sustainability monitoring
Yalcinkaya and Singh (2015)	Several databases like Elsevier, ProQuest, Emerald, EBSCO, etc.	– Identified 12 core BIM research areas – Identified 90 BIM factor labels or keywords.
Zhao (2017)	Web of Science	– Identified ten (10) co-citations clusters – Identified 7 hot topics in BIM research – Identified 5 research areas with most citations
Santos *et al.* (2017)	Web of Science and other unlisted databases	– Proposed 9 research categories – Identified research areas and journals with most citations – Identified current trends in BIM
Current study	Web of Science	– Identify funding (grants) structure for BIM research (*country analysis and research category analysis*) – Identify the salient research methodology employed in past BIM researches – Identify the network of BIM publication by research origin and geographical scope – Propose a much concise and precise core research category (10) and areas (107) – Identify relevant BIM software, data schema, and project areas for BIM application – Classify BIM publications based on project sectors they focused on (such as energy, transportation, etc.)

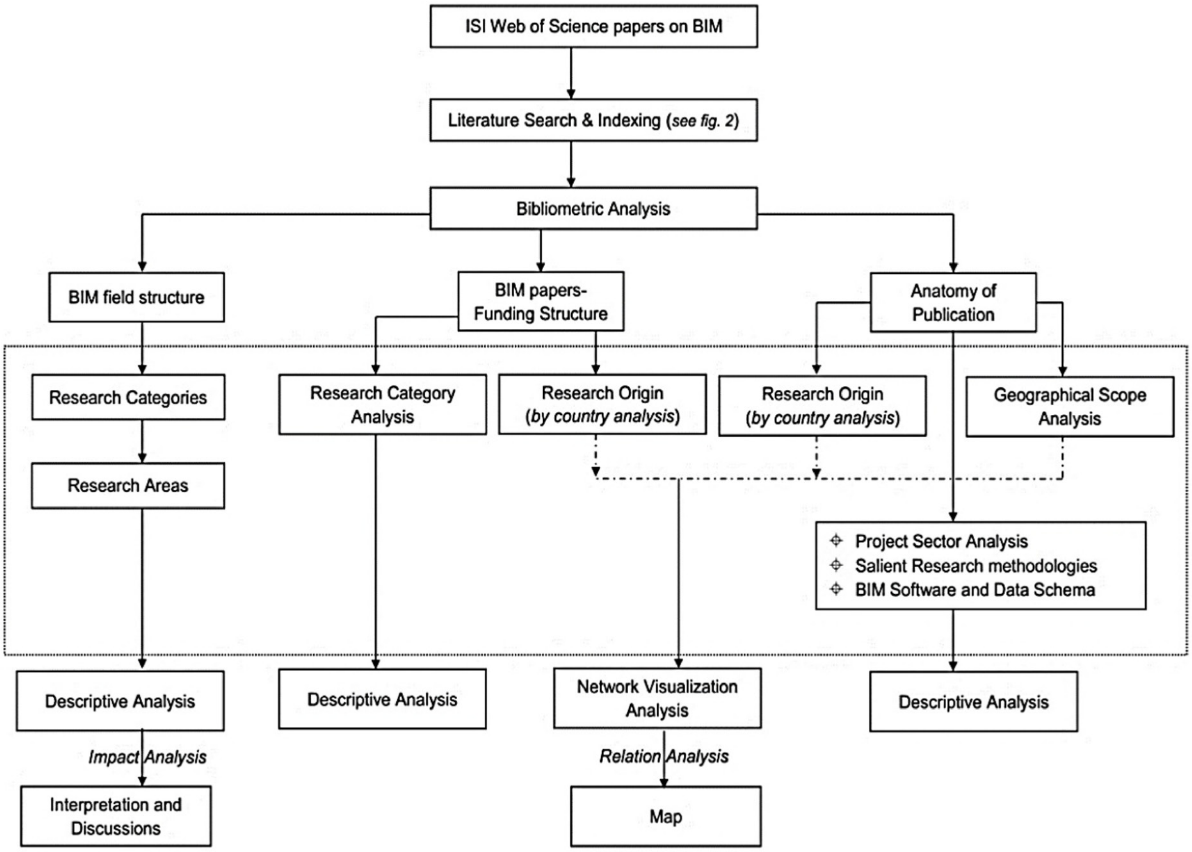

Fig. 1. Outline of research design

publications, however, there is a considerable overlap in their records. Moreover, Google Scholar seems to have a more extensive collection of publications than both Scopus and Web of Science. However, Google Scholar is noted to contain many incorrect publication attributions, as an author with the same first initial and last name may be attributed more citations. Also, Google Scholar also has another minor problem with indexing of articles, as it counts all conference abstracts which has nothing to do with citations, thereby increasing the numbers of papers very dramatically.

However, for this study, a comprehensive search as detailed in Figure 2 was carried using the ISI Web of Science database because of its "*comprehensiveness, organized structure and scientific robustness*" (Neto *et al.* 2016). Marsilio *et al.* (2011) also argued that it is the "*most commonly used and generally accepted source for bibliometric studies*". The search keywords are: "*Building Information Modelling*", "*BIM*" and "*Building Information Modeling*".

The selected time span is between 1990 and 2016 equivalent to 26 years. The research corpus only comprises of articles published in a journal instead of a doctoral thesis (*since most of them are afterward published in journals*), books or conference papers. Moreover, authors do publish their work in scholarly journals because they are classified as "certified knowledge" (Ramos-Rodríguez, Ruíz-Navarro 2004) and have gone through a peer-review process. The search results gave 567 journal articles. However, 122 papers were excluded from further analysis as they fail to meet the inclusion criteria (see Table 3) due to several reasons such as abstracts written in a language other than English (*12 articles*). We also have three articles with no abstracts and 107 articles found to be unrelated to research (such as

Table 3. Indexed corpus profile

Profile	Number of papers	Percentage (%)
Total publications in web of science	567	100
Abstracts which are written in languages other than English	12	2.12
Papers excluded for not having abstracts	3	0.53
Papers excluded for being registered twice	0	0
Papers excluded for not being related to the research area/topic	107	18.87
Total papers excluded before analysis	122	21.52
Total papers to be analyzed for this guided study research	445	78.48

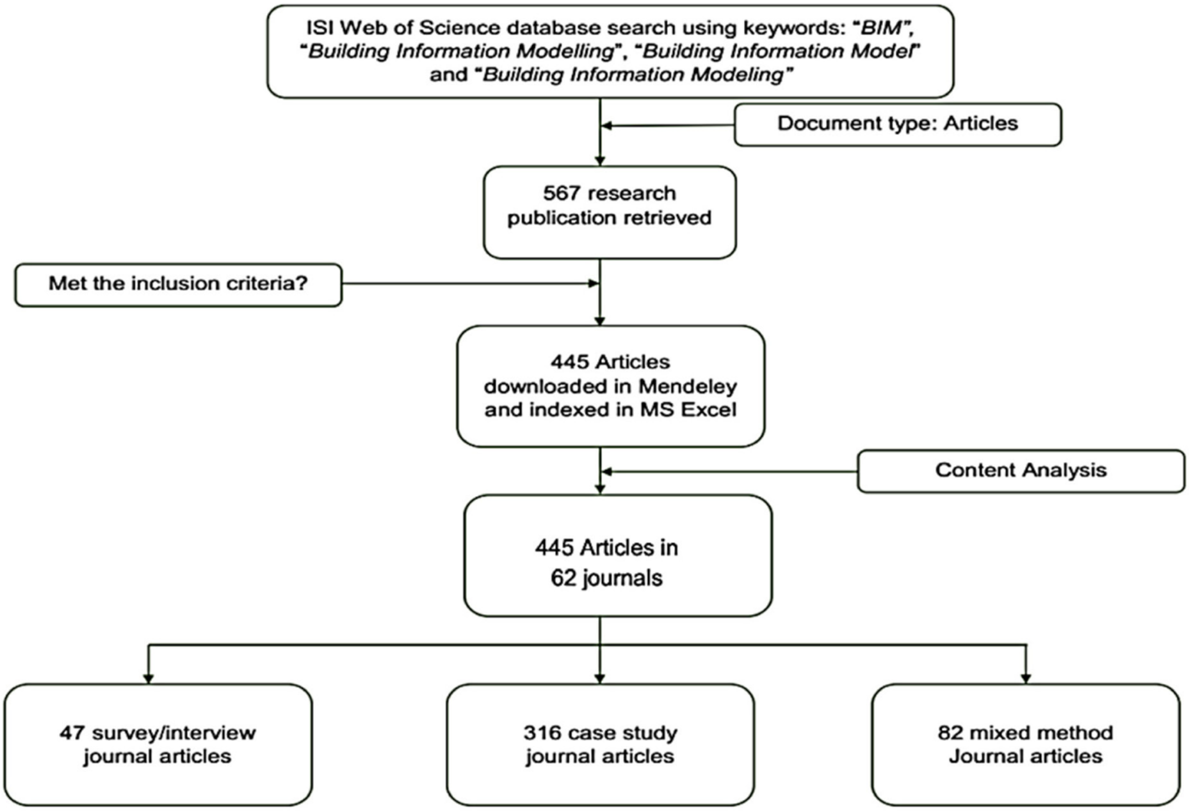

Fig. 2. Literature search and indexing approach

papers that only refer to BIM but cannot be related to any of the categorized research areas). A total 445 articles which were downloaded in Mendeley Desktop (*reference manager*) and indexed in the Microsoft Excel program. The indexed articles consisted of 316 case studies papers, 47 surveys/interviews articles, and 82 articles which utilized mixed method research approach.

3. Bibliometric analysis

This section discusses the facets and results of this study of bibliometric analysis. These include (i) descriptive analysis of published research in BIM; (ii) defining the BIM subfields and research areas; (iii) BIM funding structure; and (iv) the anatomy of the BIM publications as outlined in this study research design.

3.1. Published research in BIM

The volume of published research in BIM has notably increased in recent years (Santos *et al.* 2017); since it has emerged as a key, and innovative approach to construction and civil engineering (Yalcinkaya, Singh 2015) and these studies covers diverse areas including several technical and non-technical issues (Zhao 2017). More so, in the last four years, more than 75 percent of BIM articles were published.

The literature used in this bibliometric analysis are journal articles, and all but one of the journal has no impact factor (IF). The analysis of the journals reveals that 36 out of the 62 journals (58 per cent) has an impact factor (IF) greater than 1.000 while 16 journals have IF value between 0.500 and 0.999 representing 26 per cent and the rest of 9 journals are below 0.500 IF value. Meanwhile, an analysis of BIM publishing journals reveals several concepts and issues revolving around the BIM research field; also 32 out of the 62 journals (52 per cent) published just one article. More so, another cluster of 20 journals published between 2 and 6 papers; meanwhile, there is another group of ten (10) journals whose number of published articles on BIM is 10 articles or more (see Table 4).

The structure of the published research on BIM closely followed the "Pareto-principle" also known as the 80/20 rule (Brynjolfsson *et al.* 2011; Pareto 1964). In this study, it follows that 349 articles (78.4 percent) are published in just 10 journals (16 per cent) which can be termed a 78/16 rule which aligns with the Pareto postulation; the average impact factor for the 10 journals whose publications followed the Pareto principles is 1.568. More so, from year 2012 to date the number of published articles on BIM have significantly increased with more volumes of articles coming from journals such as "Automation in Construction", "Advanced Engineering Informatics", and "Journal of Computing in Civil Engineering".

Table 4. BIM journal publication lists and impact factors

S/N	Journals	Total	Impact factor	S/N	Journals	Total	Impact factor
1	Applied Energy	2	5.746	32	IEEE Transactions on Engineering Management	1	1.103
2	Environmental Science and Technology	1	5.393	33	International Journal of Precision Engineering and Manufacturing	1	1.075
3	Computer-Aided Civil& Infrastructure Engineering	5	5.288	34	Journal of Bridge Engineering	1	1.069
4	Journal of Cleaner Production	1	4.959	35	Sustainable Cities and Society	3	1.044
5	Waste Management	1	3.829	36	Scientia Iranica	1	1.025
6	Building and Environment	6	3.394	37	Structural Design of Tall and Special Buildings	1	0.898
7	Resource Conservation and Recycling	2	3.280	38	Journal of Performance of Constructed Facilities	2	0.893
8	Energy Policy	1	3.045	39	HVAC&R Research	2	0.871
9	Expert Systems with Applications	1	2.981	40	Journal of Transportation Engineering	1	0.801
10	Energy and Buildings	10	2.973	41	Journal of Industrial and Management Optimization	1	0.776
11	IEEE Transactions on Intelligent Transportations System	1	2.534	42	Transportation Research Record	1	0.770
12	Automation in Construction	177	2.442	43	Journal of Asian Architecture and Building Engineering	11	0.750
13	Construction and Building Materials	2	2.421	44	Journal of Environmental Protection and Ecology	1	0.734
14	Applied Mathematical Modelling	1	2.291	45	Studies in Informatics and Control	1	0.723
15	Building Research and Information	2	2.196	46	Mathematical Problems in Engineering	1	0.689
16	Safety Science	4	2.157	47	KSCE Journal of Civil Engineering	10	0.600
17	Carbon Management	1	2.092	48	Canadian Journal of Civil Engineering	6	0.586
18	Advanced Engineering Informatics	40	2.000	49	Advances in Structural Engineering	1	0.577
19	Journal of Computing in Civil Engineering	36	1.855	50	International Journal of Engineering Education	2	0.559
20	Journal of Management in Engineering	14	1.840	51	Journal of Professional Issues in Engineering Education and Practice	11	0.538
21	Journal of Building Performance Simulation	1	1.807	52	PCI Journal	1	0.526
22	Research in Engineering Design	1	1.786	53	Proceedings of the Institution of Civil Engineers-Structures and Buildings	1	0.429
23	Measurement	1	1.742	54	International Journal of Civil Engineering	1	0.372
24	Advances in Engineering Software	3	1.673	55	Proceedings of the Institution of Civil Engineers- Civil Engineering	2	0.348
25	Journal of Civil Engineering and Management	14	1.530	56	Journal of the Chinese Institute of Engineers	4	0.246
26	Engineering with Computers	1	1.460	57	Research Journal of Chemistry and Environment	1	0.240
27	Building Simulation	3	1.409	58	Informes de la Construccion	3	0.227
28	Sustainability	3	1.343	59	Ashrae Journal	5	0.223
29	International Journal of Computer Integrated Manufacturing	1	1.319	60	Gradevinar	3	0.158
30	Structure and Infrastructure Engineering	1	1.202	61	Civil Engineering	1	0.153
31	Journal of Construction Engineering and Management	26	1.152	62	Intelligent Computing in Engineering and Architecture	1	N/A
		363				82	
	Total	445					

Note: Year (*Number of Publications*) – 2006 (2), 2007 (3), 2008 (7), 2009 (6), 2010 (17), 2011 (32), 2012 (28), 2013 (63), 2014 (96), 2015 (114), 2016 (77).
N/A – Not available Impact Factor as at year 2016.

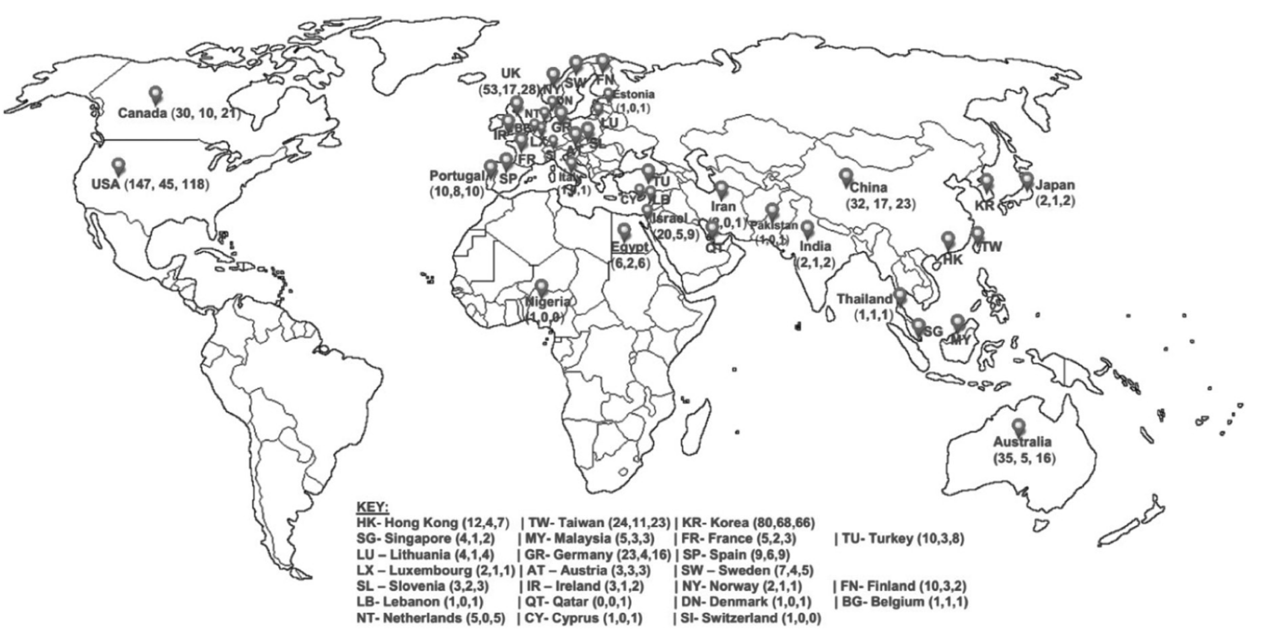

Fig. 3. Map network visualization analysis (funding structure)

3.2. BIM sub-fields and research areas

The next stage in the bibliometric analysis is to define the BIM sub-fields (research categories and research areas). We identify ten (10) research categories namely "IT-enabled simulations and visualization"; "building design and energy conformance"; "BIM software & data schema"; "BIM model development"; "BIM learning, adoption & practice"; "construction and project management"; "safety and risk management"; "facility management"; "sustainability-related studies"; and "literature review" (see Table 5).

The establishment of the semantic link and classification of the published works to the ten (10) research categories was based on a directed content analysis approach using articles keywords, titles, scope covered and the research findings. Meanwhile, further clustering of the articles enables us to define one hundred and ten (107) research areas/themes based on the ten research categories. The analysis of the research categories reveals a prevalent of publication in aspects such as "construction and project management" with 78 articles; "BIM learning, adoption & practice" with 70 articles; and "building design and energy conformance" with 65 articles which sums up close to fifty (50) percent of all published works in BIM. The defined category in this study is more concise and specific than previous studies, although there is a partial overlap when compared with those provided by previous authors (Yalcinkaya, Singh 2015; Zhao 2017).

Table 5. BIM research categories

Code	BIM- Research Categories	Number of articles
RC1	IT-enabled simulations and Visualisation	40
RC2	Building design and Energy conformance	65
RC3	BIM Software & Data schema	54
RC4	BIM model development	52
RC5	BIM learning, adoption & practice	70
RC6	Construction and Project Management	78
RC7	Safety / Risk Management	31
RC8	Facility management	37
RC9	Sustainability	17
RC10	Literature review	1

Furthermore, for the research areas, one hundred and ten (107) themes were identified (see Table 6) through an iterative process whereby identified themes are grouped in a cluster under each research category. After the loading of the research themes into the research categories, three research areas – "construction and project management" with 18 themes, "facility management" with 17 themes and "BIM model development" with 16 themes are the most represented research areas. It can be deduced from the analysis that BIM has found more application in research in construction and project management with more published articles and themes, this is because of diverse use in the construction industry (Zhao 2017); and the fact that more contractor has started making use of BIM (Fan *et al.* 2014). Further discussion on the research categories and areas are outlined in Section 4 of this study.

3.3. BIM publications' funding structure

BIM disciplinary field is a technologically backed research area which requires researchers to experiment

Table 6. Theme loading for the BIM research areas

Code (research category)	Research areas/themes	Number of themes
RC1	RC1.1 – Emergencies sensing localization RC1.2 – Real-time and 3D visualizations RC1.3 – Fire safety simulations RC1.4 – Point-cloud data extraction RC1.4 – Automated or semi-automated generation of data RC1.5 – Virtual support systems RC1.6 – Synchronous online collaboration.	6
RC2	RC2.1 – Building energy regulations RC2.2 – Code checking & compliance RC2.3 – Building envelope cost and energy performance RC2.4 – Energy management and analysis RC2.5 – Structural analysis and design RC2.6 – Building rating systems and assessments RC2.7 – Tracking of design changes and errors RC2.8 – Daylighting profiling RC2.9 – Design validation and coordination.	9
RC3	RC3.1 – Interoperability RC3.2 – Usefulness, benefits, and limitations of BIM applications RC3.3 – Augmented reality system RC3.4 – Industry Foundation Class (IFC) RC3.5 – BIM & Semantic web interoperability RC3.6 – Semiotic User interface analysis RC3.7 – Cost Estimating BIM tools RC3.8 – Software coupling RC3.9 – BIM data exchanges RC3.10 – Mobile BIM RC3.11 – Data schemas (GbXML, City GML, MVD, etc.).	11
RC4	RC4.1 – Quantity take-off RC4.2 – As-built BIM creation RC4.3 – Domain vocabulary & Ontology development RC4.4 – Model validation process RC4.5 – Cloud-BIM RC4.6 – BIM collaborative system RC4.7 – Semantic web technology RC4.8 – Physical BIM library RC4.9 – Scan-to-BIM techniques RC4.10 – Open query language for BIM RC4.11 – nD developments RC4.12 – Mapping of BIM & domain knowledge RC4.13 – Discrete Event Simulation (DES) model RC4.14 – Information extraction RC4.15 – Topological information extraction model RC4.16 – Java-based BIM.	16
RC5	RC5.1 – BIM usage and adoption RC5.2 – BIM curriculum development RC5.3 – Construction stakeholders' BIM adoption strategies RC5.4 – BIM teaching and support RC5.5 – Drivers of BIM adoption RC5.6 – Cost-benefit analysis of BIM implementations RC5.7 – BIM adoption barriers RC5.8 – BIM standardization & Intellectual property rights RC5.9 – BIM competency assessment RC5.10 – BIM ethics & professionalism RC5.11 – BIM practice paradigms & governance approach.	11
RC6	RC6.1 – Construction planning and monitoring RC6.2 – Schedule optimization RC6.3 – BIM governance platform RC6.4 – Material management & quality assessment RC6.5 – Waste management RC6.6- Supply chain management RC6.7 – Lean construction management & BIM RC6.8 – Construction sequencing & logistics optimization RC6.9 – Real-time progress management RC6.10 – Labour productivity assessment RC6.11 – Automated, rule-based constructability checking RC6.12 – 3D compliance checking RC6.13 – Project cost control RC6.14 – Project delivery and asset management RC6.15 – Construction knowledge management RC6.16 – BIM-based procurement framework RC6.17 – RCE-procurement RC6.18 – Construction collaborative networks.	18
RC7	RC7.1 – Automated safety planning and management RC7.2 – Risk knowledge management RC7.3 – Walkability & hazardous area identification RC7.4 – Site risk identification RC7.5 – Search & Rescue algorithm RC7.6 – Fire safety management RC7.7 – Workspace safety and requirements RC7.8 – Automatic safety checking of construction models.	8
RC8	RC8.1 – Automated access control RC8.2 – Defect management system RC8.3 – Earthquake damage assessment RC8.4 – Performance-based maintenance RC8.5 – FM data extraction & conversion RC8.6 – Indoor emergency response facilitation RC8.7 – Virtual retrofit RC8.8 – Tracking the built status of MEP works R8.9 – Failure root-cause detection RC8.10 – Security analysis RC8.11 – Localization of RFID-equipped assets RC8.12 – Handover model RC8.13 – Building maintenance RC8.14 – Energy retrofitting RC8.15 – Facilities lifecycle information on RFID tags RC8.16 – Heat flow modeling RC8.17 – Image-based verification of as-built documentation.	17
RC9	RC9.1 – Sustainability performance of building RC9.2 – Environmental impact evaluation RC9.3 – Integrating BIM & LEED RC9.4 – Sustainable energy usage RC9.5 – BIM-based decision support for master planning RC9.6 – Sustainability Appraisal (steel design) RC9.7 – Indoor environmental quality (IEQ) RC9.8 – Sustainable design and construction RC9.9 – 3D analysis of lifecycle assessment RC9.10 – Sustainable material selection.	10
RC10	RC10.1 – Pattern and trend in BIM research.	1

with, develop and interoperate various BIM software and tools of which many of them are only commercially available and expensive, hence this section attempts to investigate the funding arrangement used in the various journal articles.

The bibliometric analysis in this section focuses on reviewing the funding structure (i) based on research category analysis, and (ii) research origin analysis (author & co-authors' affiliations). An analysis of the funding structure reveals a steady increase in the number of BIM research receiving some form of funding or grants to carry out the relevant studies (from 20 articles in 2011 to 67 articles in 2015); also, more than half (51 percent, #231 articles) received funding. Meanwhile, based on an analysis of the research categories which received more funding, we identified four (4) research categories which have more than thirty (30) funded articles, and these include: RC2 – "Building design and Energy conformance" which 40 funded articles, RC6 – "Construction and Project Management". Others are RC3 – "BIM Software & Data schema", and RC4 – "BIM model development" with 39, 35 and 32 funded articles respectively which represent more than 60 percent of the funded articles of all BIM research categories (see Table 7).

More so, the analysis of the funding structure of BIM publication (based on research origin analysis) was analyzed using a mapped network visualization technique as shown in Figure 3. The funding arrangement for any given article was based on the information provided by the author(s) in the acknowledgment section of the published paper. The format for the map network visualization analysis in Figure 3 is based on "Country" ("articles per research origin", "funded articles", "articles per geographical scope"). Therefore, by "articles per research origin" we imply the number of articles published by the author(s) or co-author(s) affiliated with an institution based in that country. More so, the term "articles per geographical scope" implies the number of articles with originating data or case studies based in that country. A bibliometric analysis of public-private partnership (PPP) by Neto *et al.* (2016) also used the terms "research origin" and "geographical scope" to portray similar expressions.

Table 7. Funding structure

Year	Funded articles	Percent (%)	Research categories	Funded articles	Percent (%)
2016	40	17.3	RC1	21	9.1
2015	67	29	RC2	40	17.3
2014	46	19.9	RC3	35	15.2
2013	32	13.9	RC4	32	13.9
2012	10	4.3	RC5	26	11.3
2011	20	8.7	RC6	39	16.9
2010	8	3.5	RC7	15	6.5
2009	5	2.2	RC8	16	6.9
2008	1	0.4	RC9	7	3
2007	2	0.9	RC10	0	0
2006	0	0			
Total	231	100		231	100

For example, we have USA (147,45,118) – this imply that they are 147 BIM authors/co-author(s) from the United States based on the bibliometric analysis and 45 of their BIM articles were funded, while there are 118 articles with the research data (that is, case studies, questionnaire surveys or interviews, etc.) based solely in the United States. BIM articles from countries namely the Republic of Korea, the US and China, have more funded articles with 68, 45 and 17 articles than any other countries which represent a combined 56 percent of all funded articles. The funding of BIM projects in South Korea, and China has aided the adoption and implementation of BIM in the AEC industries of these two countries; also, BIM standards, guidelines and component families which are essential for successful BIM implementation have been developed in Korea (G-SEED) and Hong Kong (BEAM-Plus).

The relative high funding rate from the Republic of Korea is not far-fetched because as noted by Lee and Yu (2016), the Korean central government have strongly encouraged BIM usage and adoption via the promulgation of policies and funding through the National Research Foundation of Korea (NRF). Also, a recent study by Won *et al.* (2013) revealed a significant increase in the adoption rate in both USA and Korea.

3.4. Anatomy of BIM publications

This section focuses on other aspects of the anatomy of the published BIM articles as depicted in the research design. The bibliometric analysis in this section focuses on (i) project sector analysis; (ii) the salient research methodologies; (iii) related BIM software and data schema.

3.4.1. Project sector analysis

A bibliometric analysis of the corpus of BIM publications reveal a greater focus on the 'building and housing sector' of the built environment with a total of 347 BIM articles out of the overall 445 articles. BIM articles in the "*building and housing*" sector focuses on aspects such as "*single family houses*", "*residential floors*", "*parking garage*", "*storey buildings*", "*high-rise structures*", "*building component and elements*", "*sports center*s", and "*educational buildings*" (see Table 8). A study by Chang and Lin (2016) reveals that BIM "*is currently being applied mostly to buildings*" with few applications elsewhere. Table 8 outlines the project sectors covered by the BIM publication corpus as deduced through this study's bibliometric analysis; meanwhile, aspects covered by the articles under each project sectors were defined.

3.4.2. Salient research methodologies

The bibliometric analysis of the articles' corpus in this section focus on defining the primary research design and

Table 8. Articles' project sector analysis

Project Sector	Aspects covered	Number of articles
Building and Housing	Single family houses; Residential floors; Parking garage; Storeys buildings; High-rise structures; Building component and elements, Sports center, Educational buildings	347
Transportation	Bridges; Highways; Tunnel construction; Subways; Airports; Subway stations; Railways; Railway tracks	17
Environment	Safe walking environment; Safety; Traffic noise control; Earthquake damage assessment; Waste effectiveness; Hazard identification & prevention; Safety planning; Work-Space Planning	24
Education	BIM curriculum development; BIM implementation; BIM in Quantity Surveying practice; BIM teaching; Developing Students' Collaborative Skills; Course developments	22
Energy infrastructure	Natural gas plant construction; Gas pipeline; Renewable energy system	5
General	Applies to all project sectors (Procurement, Estimating, Construction projects & Built environment)	28
Urban regeneration	Post-earthquake operations (such as search and rescue, and damage assessment)	2

Table 9. BIM software and data schema

BIM software category	Software (frequency of mentions or usage)	Number
Data Schema	Industry Foundation Classes [IFC] – 187; GbXML [green building XML] – 30 MVD [model view definitions] – 22; IFCXML – 22; AecXML – 5; City GML – 4; Omni class – 2; NBDM [TrySys] – 1; bcXML – 1; LandXML – 1; EcoXML – 1	11
Architectural and Structural tools	Autodesk Revit – 132; Graphic Soft ArchiCAD – 67; AutoCAD – 28; Bentley Architecture systems – 26; Vico Constructor – 13; Digital Projects – 8; Nemetschek AllPlan – 8; Nemetschek Vectorworks – 4 Google SketchUp – 3; Autodesk Inventor – 1	10
Building Energy Analysis & Simulation Tools	Energy Plus – 24; Ecotect – 17; IES VE – 10; eQuest – 10; DOE-2.2 – 7; Radiance – 6	6
Estimating Tools	Quantity take-off – 3; On-screen take-off – 2; Innovaya – 2; BuildSoft Estimating software – 1; CATO CAD – 1; Estimator – 1	6
Structural Tools*	Tekla structures – 30; SAP – 2; MIDAS – 2; STAAD Pro V8i – 1; ADAPT (Structural Concrete Software) – 1	5
Construction Management Tools	Navisworks – 27; MS Excel – 13; MS Project – 11; DProfiler – 3	4
Sustainability Analysis	Green Building Studio – 13; IES Virtual Environment – 10; Project Vasari – 1	3
Model Viewer	Solibri Model Viewer – 32; Bentley Micro Station – 13	2
Geographic Information System	ESRI's ArcGIS – 4	1
Ontology Development Tools	Protégé – 2	1

approaches utilized by previous BIM authors. An analysis of the articles reveals that 316 articles out of 445 BIM articles (i.e. 71 percent) utilize the case study as the research method, this implies that BIM articles' authors prefer case study approaches in their studies. Basbagill *et al.* (2013) argued that case study research design is the best approach to introduce new concepts to industry practice and since BIM is still relatively new to the construction industry; and this can be adduced as the reasons behind the use of case studies for BIM researches.

More so, Davies and Harty (2013) believed case study research method does help to challenge fundamental misconceptions when applying innovative technologies to practice; although, case study approach has no need for internal validation (Hartmann *et al.* 2012). Furthermore, the analysis of the articles' corpus shows that "questionnaire surveys and interviews" research approaches with 47 articles (11 percent) and "general discourse and literature reviews" approaches with 38 articles (8 percent) are also quite common among BIM authors.

3.4.3. BIM software and data schema

The bibliometric analysis of the BIM articles in this section assesses the frequency of usage and mentions of different BIM software and data standard as analyzed from the BIM publications' corpus. An analysis of the articles reveals that there are eleven (11) BIM data schemas in use in the construction industry; and in fact, the industry foundation class (IFC) and the green building eXtensible markup language (gbXML) are very popular among BIM authors with 187 and 30 mentions in the articles' corpus (see Table 9). However, of the two interoperability standards, IFC is mainly employed in the AEC industry (Belsky *et al.* 2014; Karan, Irizarry 2015; Tashakkori *et al.* 2015).

More so, the high usage of the IFC schema is because of its continuous improvement so as to advance interoperability among BIM software (Kota *et al.* 2014), although it is not yet at a satisfactory level (Aram *et al.* 2013). Meanwhile, the MVD schema is only a subset of the IFC schema (Lee *et al.* 2013). Also, the IFCXML schema is another subset of the IFC schema that allows the IFC to be transmutable over the web (Redmond *et al.* 2012). Furthermore, unlike IFC, the gbXML data schema is specifically developed for energy analysis while the IFC data format is a schema developed by buildingSMART and can be used for data exchange across the building life cycle (Kim *et al.* 2012).

Furthermore, the analysis of BIM software for architectural and structural designs reveals 10 software in use in the AEC sector, of which Autodesk Revit with 132 articles' mentions is the most used software; previous studies unveiled similar findings (see Kim *et al.* 2015a, 2015b, 2015c; Wang *et al.* 2015). Survey results by Bynum *et al.* (2013) revealed that Revit is the dominant BIM authoring tool in the AEC industry with 78 percent of respondents utilizing it. However, there was low usage of BIM energy analysis software such as Ecotect, IES Virtual Environment. Nevertheless, no single BIM application can support all the process functionalities required in the AEC industry.

4. Discussions on the BIM research categories

This section provides a semantic link between the defined BIM research categories and research areas/themes that were established in Section 3.2 with a view to providing a more qualitative analysis of the articles in alignment with the categories descriptions. Therefore, we conducted a critical appraisal of selected articles based on their relevance to the established BIM research categories.

To conserve space, we reviewed four research categories out of the ten defined BIM research categories, which are presented in the following sub-sections. Moreover, a total of 175 articles were examined in the section.

4.1. Construction and project management (RC6)

The research category "construction and project management" (RC6) is the most trending BIM sub-field (with 78 articles) among the ten identified research categories, and it also has the highest number of research areas with 18 themes as seen in Tables 5 and 6. Trending topics in this field include *RC6.1* – "*construction planning and monitoring*" (Faghihi *et al.* 2016; Kim *et al.* 2014, 2016a); *RC6.2* – "*schedule optimization*" (Altaf *et al.* 2014; Chen *et al.* 2013; Faghihi *et al.* 2014; Gelisen, Griffis 2014; Kang *et al.* 2016; Kim *et al.* 2013; Liu *et al.* 2015a; Moon *et al.* 2014; Tserng *et al.* 2014; Wang *et al.* 2014a); *RC6.3* – "*BIM governance platform*" (Dossick, Neff 2010; Farr *et al.* 2014; Knight 2008); *RC6.4* – "*Material management & quality assessment*" (Chen, Luo 2014; Francom, El Asmar 2015; Kim *et al.* 2015e), and *RC6.5* – "*Waste management*" (Akinade *et al.* 2015; Liu *et al.* 2015c; Porwal, Hewage 2012; Won *et al.* 2016).

More so, other research areas focus on *RC6.6* – "*supply chain management*" (Babic *et al.* 2010; Irizarry *et al.* 2013; Lu *et al.* 2016); *RC6.7* – "*lean construction management & BIM*" (Dave *et al.* 2016; Sacks *et al.* 2010a, 2010b); *RC6.8* – "*construction sequencing & logistics optimization*" (Han *et al.* 2015; Kumar, Cheng 2015; Marzouk, Abubakr 2016); *RC6.9* – "*real-time progress management*" (Kim *et al.* 2013; Matthews *et al.* 2015); *RC6.10* – "*labour productivity assessment*" (Lee *et al.* 2014; Poirier *et al.* 2015); and *RC6.11* – "*automated rule-based constructability checking*" (Hu *et al.* 2016; Nahangi, Haas 2016).

Furthermore, other research themes under RC6 are *RC6.12* – "*3D compliance checking*" (Jiang, Leicht 2015; Nahangi, Haas 2014); *RC6.13* – "*project cost control*" (Turkan *et al.* 2013; Wang *et al.* 2014b); *RC6.14* – "*project delivery and asset management*" (Choi *et al.* 2014; Tsai *et al.* 2014a); *RC6.15* – "*construction knowledge management*" (Lin 2014; Peterson *et al.* 2011; Wang, Leite 2016); *RC6.16* – "*BIM-based procurement framework*" (Goedert, Meadati 2008); *RC6.17* – "*RCE-procurement*" (Grilo, Jardim-Goncalves 2011, 2013), and *RC6.18* – "*construction collaborative networks*" (Abedi *et al.* 2016; Grilo *et al.* 2013; Neath *et al.* 2014).

Furthermore, Fan *et al.* (2014) carried out eight (8) case studies research to assess the effect of BIM on construction projects on aspects such as request for information (RFI), reworks, schedule compliance and change orders. The findings of the case studies reveal a marked reduction in the RFI between 50 and 90 percent, fewer or no modification(s), and compromises in the project with improved quality. More so, there was more accurate schedule compliance with shorter duration and altogether less reworks and significantly fewer change orders. Meanwhile, to facilitate real-time visualization of BIM models; Johansson *et al.* (2015) developed a prototype BIM viewer. Tan *et al.* (2017) use the genetic algorithm (GA) technique to optimize for the visualization of lift planning in offshore rigs. Other studies include BIM for infrastructural projects (Bradley *et al.* 2016), the development of a prototype BIM-GIS architecture to facility management practices (Kang, Hong 2015); the use of geospatial and semantic technologies for pre-construction operations (Karan, Irizarry 2015), BIM for quality assurance (Kim *et al.* 2016c); BIM for work sequencing (Kim *et al.* 2016b); project progress and productivity improvement (Matthews *et al.* 2015; Nath *et al.* 2015), and BIM for as-built documentation (Park, Cai 2017).

In summary, there has been a significant increase in the number of publications classified under the labeled theme "*construction and project management*" between 2013 and 2016, in fact, 65 out of the 78 BIM articles under this research area were published during this period. More so, of the 18 BIM research areas under RC6, we have four themes with more than 6 articles, these include *RC6.2* – "*schedule optimization*" with 11 articles, *RC6.9* – "*real-time progress management*", *RC6.18* – "*construction collaborative networks*" and *RC6.15* – "*construction knowledge management*" with 9, 6 and 6 BIM articles respectively.

The review and analysis of the BIM articles reveals the benefits of BIM in construction and project management as (1) to facilitate collaboration and coordination among construction stakeholders; (2) to optimize the construction schedule; (3) to track the progress of work on site; and (4) to serve as hub or central house for the management of construction information and processes.

4.2. BIM learning, adoption & practice (RC5)

The next identified BIM research category is "*BIM learning, adoption & practice"* with 70 BIM articles and under this category are 11 research area/themes as shown in Tables 5 and 6. Without the framework to aid and strengthen the implementation of innovative technology, approaches or techniques in a diverse and competitive industry like the construction industry such technology or approach may not seek the light of the day. The previous statement enforces the importance of BIM paper in this research category.

More so some of these studies and research themes covered include: *RC5.1* –"*BIM usage and adoption*" (Eadie *et al.* 2013; Fortner 2008; Gilkinson *et al.* 2015; Kim *et al.* 2016d); *RC5.2* – "*BIM curriculum development*" (Pikas *et al.* 2013; Sacks, Pikas 2013; Sampaio 2015; Solnosky *et al.* 2014; Wu, Issa 2014); *RC5.3* – "*construction stakeholders' BIM adoption strategies*" (Ahn *et al.* 2016; Jung, Lee 2016; Salleh, Fung 2014; Xu *et al.* 2014); *RC5.4* – "*BIM teaching and support*" (Gnaur *et al.* 2015; Kim 2012; Kovacic *et al.* 2015; Sacks, Barak 2010); *RC5.5* – "*drivers of BIM adoption*" (Mom *et al.* 2014; Tsai *et al.* 2014b); *RC5.6* – "*cost-benefit analysis of BIM implementations*" (Giel, Issa 2013; Lu *et al.* 2014).

Other research themes in this research category are *RC5.7* – "*BIM adoption barriers*" (Chien *et al.* 2014; Watson 2011); *RC5.8* – "*BIM standardization & intellectual property rights*" (Fan 2014; Howard, Björk 2008; Kraatz, Hampson 2013); *RC5.9* – "*BIM competency assessment*" (Giel, Issa 2016; Succar *et al.* 2013; Wong *et al.* 2014, 2015); *RC5.10* – "*BIM ethics & professionalism*" (Jaradat *et al.* 2013; Love *et al.* 2015; Succar 2009); and *RC5.11* – "*BIM practice paradigms & governance approach*" (Alreshidi *et al.* 2016; Becerik-Gerber, Kensek 2010; Hanna *et al.* 2013, 2014; Rezgui *et al.* 2013; Samuelson, Björk 2016; Taylor, Bernstein 2009; Won, Lee 2016).

A study by Lee and Yu (2016) compared the acceptance level of BIM in South Korea and the United States of which the data were collected using interviews and questionnaire surveys. Their findings revealed a higher adoption and user satisfaction rate in the US than those in South Korea. More so, an ethnography research conducted by Mahalingam *et al.* (2015) on two metro railway stations projects in India, exemplified the effect of BIM in the decision-making process leading to precise planning and reduced contract duration. The rapid growth in BIM adoption in the Swedish construction industry was elucidated in a study by Samuelson and Björk (2014) while Zhang *et al.* (2016) developed a framework to facilitate the integration of BIM and sustainability studies into the curriculum development for civil engineering students. Also, some set of principal areas or factors to consider in the adoption and implementation of BIM in an organization has been developed (Won *et al.* 2013).

Conclusively, there have been a steady increase in the number of BIM articles published under the category – "*BIM learning, adoption & practice*" between 2013 and 2016; however, prior to this period, less than four BIM articles in this research area were disseminated. Meanwhile, BIM research in this category had focused mostly on *RC5.1* – "*BIM usage and adoption*" and *RC5.11* – "*BIM practice paradigms & governance approach*" (with 13 articles each); we can then surmise that BIM being a novel approach in the built environment has led BIM authors to direct their attention to the core of its adoption and practice and to set up a governance mechanism to facilitate its implementation. Next, are research themes such as *RC5.2* – "*BIM curriculum development*" and *RC5.4* – "*BIM teaching and support*" with 7 articles each; this analysis reveals the increasing spotlight on the development of BIM module and training for undergraduate university students and professionals who would be the fulcrum in the adoption and implementation of BIM.

Therefore, based on the analysis of this category, we deduce the critical drivers of BIM adoption to include: (1) The development of undergraduate BIM curriculum and modules which should incorporate the practical aspects of BIM to train students who are potential "recruits" to the industry. (2) The institution of a training and support programs such as workshops, seminars, and conferences on BIM to aid the skill sets and development of in-house personnel on the use of BIM. (3) Establishment of a working BIM governance mechanism or framework to support its overall implementation and increase the success rate of BIM-enable projects.

4.3. Building design and energy conformance (RC2)

The research category of "*Building design and Energy conformance (RC2)*" is another major area of immense publication and interest among BIM authors and in the construction industry with 65 BIM articles as at the year 2016. The bibliometric analysis of its research areas and themes crystallize out nine (9) main BIM research themes which are: *RC2.1* – "*building energy regulations*" (McGuire *et al.* 2016; Thompson, Bank 2010); *RC2.2* – "*code checking & compliance*" (Dimitrov, Golparvar-Fard 2015; Jung *et al.* 2015; Li *et al.* 2014); *RC2.3* – *"building envelope, cost and energy performance"* (Ahn *et al.* 2014; Asl *et al.* 2015; Chardon *et al.* 2016; Gökçe, H. U., Gökçe, K. U. 2013; Migilinskas *et al.* 2016); and *RC2.4* – "*energy management and analysis*" (Gökce, H. U., Gökce, K. U. 2014a; Kim, Anderson 2013; Kim, Yu 2016a; Lee *et al.* 2016).

Meanwhile, other preeminent research themes in this category include: *RC2.5* – "*structural analysis and design*" (Bosché, Guenet 2014; Ham, Golparvar-Fard 2015; Lee *et al.* 2012a; Marzouk, Abdelaty 2014b); *RC2.6* – "*building rating systems and assessments*" (Basbagill *et al.* 2013; Oti *et al.* 2016; Ryu, Park 2016); *RC2.7* – "*tracking of design changes and errors*" (Dong *et al.* 2014; Lee *et al.* 2015a; Pilehchian *et al.* 2015); *RC2.8* – "*daylighting profiling*" (Welle *et al.* 2012), and *RC2.9* – "*design validation and coordination*" (Gimenez *et al.* 2016; Kim, Jeon 2012; Kim, Yu 2016b; Lee *et al.* 2012b; Shin, Cho 2015). Meanwhile, a bibliometric analysis of this category reveals more BIM publications in areas such as *RC2.5* – "*structural analysis and design*" with 13 articles and *RC2.3* – "*building envelope, cost, and energy performance*" with 12 BIM articles.

Other aspects such as *RC2.9* – "*design validation and coordination*" and *RC2.4* – "*energy management and analysis*" with 12 and 10 BIM articles respectively are current research directions in this category. Authors with research interest in "*building design and energy conformance (RC2)*" tends to center the studies mostly in these four main themes; and it signifies the increasing importance of developing BIM models for projects which are of (1) high structural design and integrity; (2) validated and vetted designs; and (3) a profiled and efficient energy usage and management.

Studies such as Ham and Golparvar-Fard (2015) developed a system using the gbXML schema to improve the energy performance of buildings while query systems based on IFC schema have also been advanced (Gao *et al.* 2015; Kang 2017; Solihin *et al.* 2017). More so, Kim *et al.* (2015c) developed a physical BIM library to aid the simulation of building component thermal conditions; while Kim *et al.* (2015b) observed that most energy analysis for buildings are done when the design has been completed. Hence, they developed an IFC framework to map building materials with energy properties of which the results shows "significant gain in accuracy". Meanwhile, H. U. Gökçe and K. U. Gökçe (2014b) introduced an efficient integrated energy platform for the residential buildings, while Shiau *et al.* (2012) utilized Ecotect software to improve the energy usage of old structures; and studies such as Cho *et al.* (2014) and Knight *et al.* (2010) discusses the benefits of BIM in HVAC design and placement of reinforcement bars in concrete slabs respectively. Other researches focus include case studies reviews on structural BIM (Robinson 2007); quantitative assessment of carbon-dioxide emission (Jun *et al.* 2015); strategies for design error management (Al Hattab *et al.* 2015); creation of BIM models from laser scanner data (Xiong *et al.* 2013), and the design of track alignment using BIM (Huang *et al.* 2011).

4.4. Sustainability (RC9)

Sustainability is one of the increasing and preeminent issues in the construction industry and in other sectors of the global economy, while the concept of sustainable development represents a pyramid shift in the three-wheel drive of construction projects otherwise known as the "project management triangle" which are the time, cost and quality. The adoption and implementation of sustainable practices in construction ensure such projects meets its environmental, social and economic needs, considerations and implementation. BIM publications in this category are on the increase since the year 2011 till date with ten (10) main research themes has identified by the bibliometric analysis of this category articles' corpus.

The predominant research areas in this category include: *RC9.1* – "*sustainability performance of building*" (Jrade, Jalaei 2013; Kreiner *et al.* 2015); *RC9.2* – "*environmental impact evaluation*" (Lee *et al.* 2015b); *RC9.3* – "*integrating BIM and LEED*" (Azhar *et al.* 2011; Jalaei, Jrade 2015; Wu, Issa 2015); *RC9.4* – "*sustainable energy usage*" (Azzi *et al.* 2015; Liu *et al.* 2015a); *RC9.5* – "*BIM-based decision support for master planning*" (Kim *et al.* 2015d); *RC9.6* – "*sustainability appraisal*" (Oti, Tizani 2015; Wong, Kuan 2014); *RC9.7* – "*indoor environmental quality (IEQ)*" (Marzouk, Abdelaty 2014a); *RC9.8* – "*sustainable design and construction*" (Bynum *et al.* 2013; Geyer 2012); *RC9.9* – "*3D analysis of lifecycle assessment*" (Inyim *et al.* 2015; Kulahcioglu *et al.* 2012); and *RC9.10* – "*sustainable material selection*" (Bank *et al.* 2011).

Prominent studies on sustainability issues in construction projects include Oti *et al.* (2016) who utilized the BIM API extension to embed sustainability issues to simulate the assessment of structural steel design; while Oh *et al.* (2015) in a case study approach, reviewed the enhancement of the design quality of a hospital design using an integrated system. Ilhan and Yaman (2016) advanced an IFC-based sustainability decision support system ("Green building assessment tool (GBAT)") of which green building data can be certified for BREEAM (Building Research Establishment Environmental Assessment Method).

5. Research limitations

The main limitation of this study's bibliometric analysis is the literature search strategy.That is, the choice of the scientific database (ISI Web of Science) which despite being "*the world's leading citation database, offering a high level of accuracy and detail on a multidisciplinary scale*" (Neto *et al.* 2016), it may only represent a fraction of the whole population. Another drawback might evolve from the exclusion of articles not written in English and some other false positives in the removal of some unrelated papers or the categorization of items within research areas.

Conclusions

The advent of BIM in the construction industry has brought about tremendous improvement in the process and system of coordinating construction projects and enabling collaboration among professionals both in the academia and the industry. The research's objectives were to investigate and evaluate the extant literature on BIM; and identify the trends, research impacts, research categories, BIM funding structure and other parameters of the research publications' corpus through a bibliometric analysis of 445 BIM articles; which are of high impact factors from the Web of Science which Neto *et al.* (2016) regarded as the "largest and most reliable source for academic publications".

The level and depth of the bibliometric analysis is considered as the prime distinction between this study and previous literature reviews on BIM literature; which allows academics, industry practitioners and readers to track the funding structure of BIM research, the research categories and the project sectors for which BIM has had the most impact; and have an overview of how BIM literature has evolved over the years. Moreover, based on the bibliometric analysis of the BIM articles, there was a marked increase in the number of BIM articles from 17 papers in 2010 to almost double value of 32 BIM articles in 2011 and the volume of BIM publications crossed the threshold of a hundred (100) BIM papers in the year 2015 with a total of 114 published BIM articles.

Also, an analysis of the articles' corpus journal list reveals *Automation in Construction* as the journal with most published work on BIM themes. More so, the tremendous impacts of BIM implementation in the construction industry were felt most in the building and housing project sector with more than 340 BIM articles addressing issues such as building elements and components, etc. Other project areas such as transportation, environment, and even the educational sector had been positively influenced by the adoption of BIM with several articles developing frameworks, models, systems and providing innovation solutions to improve the identified sectors using BIM.

More so, after the bibliometric analysis of the BIM articles, we further endeavor to classify them into 10 research categories, and the core research categories based on published BIM works are: (1) Construction and project management; (2) BIM learning, adoption, and practice; (3) BIM design and energy conformance; (4) BIM software and data schema; and (5) BIM model development. The five research categories had more than 50 BIM articles each and are considered the salient BIM research areas. Nevertheless, research areas such as *facility management* and *sustainability* can be classified as the latest trends in BIM research with increased output in publications in those two categories since the year 2014.

Furthermore, an analysis of funding structure of BIM articles reveals that more than 50 percent of the 445 analyzed articles received some funding to undertake the research; while further funding inquiry-based research category analysis and research origin analysis reveals thus: (1) there has been a significant increase in funded articles since the year 2013 till date; (2) BIM articles relating to research categories such as "*building design and energy conformance*", "*construction and project management*", "*BIM software & data schema*" and "*BIM model development*" have received more funding (with at least 30 funded articles); (3) the Republic of Korea and the United States with 68 and 45 funded BIM publications are the countries whose BIM researchers have received a sizeable number of research grants to undertake BIM-related research. However, funding analysis by regions shows Asia with 112 articles, Europe with 57 articles and North America with 55 BIM articles are the regions with the most funded BIM publications.

Moreover, a further analysis of the research categories reveals 107 research themes. The analysis unfolds trending research themes and direction, both in the academia and in the industry and these include: "*BIM usage and adoption (RC5.1)*", "*BIM practice paradigms & governance approach (RC5.11)*"; "*structural analysis and design (RC6.9)*", "*building envelope, cost and energy performance (RC2.3)*", "*design validation and coordination (RC2.9)*"; and "*energy management and analysis (RC2.1)*" with more than 10 BIM articles each. The result is a pointer to the fact that more studies are being conducted to investigate BIM adoption and implementation in several countries and domains, and in countries where BIM has reached an acceptance level of adoption and compliance, such as the US, research tends to focus on developing and introducing BIM governance mechanisms. Other findings evaluate the salient research methodology used in previous studies and the available BIM software and data schema while the discussion centered on the established BIM research categories and themes.

However, for potential future research, researchers can select one or more research category or theme and undertake a review using the same or different research approach. The study's bibliometric analysis identified some essential gaps and opportunities for future research in BIM field. Research areas such as: (1) BIM-Sustainability issues integration; (2) Using BIM for environmental and socio-economic evaluations; (3) integrating BIM and Augmented reality during the construction phase; (4) Ontology and semantic web; (5) Mapping of BIM & domain knowledge; and (5) information extraction are currently not receiving adequate considerations from researchers in the academia and those in the industry. It is noteworthy that these research areas when given due attention have the benefits of enhancing the growth of the construction sector and boost its productivity level. Conclusively, the study would assist BIM researchers and other academics to recognize the pattern and structure of BIM research and field and help them to pinpoint areas of research interest for their future research works.

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