Collaboration on BIM-based Construction Networks: A Scientometric-Qualitative Literature Review

Abstract

BIM-based Construction Networks (BbCNs) are teams comprising members from several specialist organisations to undertake BIM-related tasks on BIM-enabled projects. Fostering collaboration within BbCNs is a top priority for construction project managers, yet no explicit body of knowledge has focused on investigating the relevant research gaps in knowledge. The present study intends to address this gap by plotting the storyline of relevant research studies in the last 10 years (2006-2016). A "*Collaboration Pentagon*" consisted of context, process, artefact, structure and agent as the theoretical lens is created through integration of relevant frameworks. The study draws upon a scientometric analysis of 1031 studies on BIM alongside the outcome of a qualitative evaluation of a total of 62 carefully selected papers on collaboration in BbCNs. The findings reveal that the scholarship on collaboration on BIM-enabled projects has predominately focused on technology as one antecedent of collaboration while project-related and managerial antecedents have remained under-researched. Moreover, though enhancing collaboration necessitates inclusion of all influential antecedents, studies with such an all-inclusive perspective are non-existent. The study contributes to the field through this inclusive *Collaboration Pentagon* and by providing a systematic and objective evaluation of available literature on collaboration in BbCNs and uncovering respective gaps.

Keywords

Building Information Modelling (BIM); Collaboration; Construction project management; Mixed methods systematic review; Scientometric analysis

1. Introduction

As one of the most influential innovations in construction industry, BIM is capable of supporting project management in procurement, construction, pre-fabrication and facility management areas (Bryde et al., 2013). Eastman (2008) (2008) defined BIM as an integrative technology with "parametric intelligence" that alters the digital building representation process throughout the lifecycle. BIM is a "multifunctional set of instrumentalities for specific purposes that will increasingly be integrated" (Miettinen and Paavola, 2014). Thus, BIM could be defined as a methodology with technological, agential and managerial components. BIM-enabled projects are typically handled by BIM-based Construction Networks (BbCNs) comprising members from specialist organisations, contracted to execute BIM-related works (Grilo et al., 2013). The ability to enhance collaboration within these BbCNs has been a selling point for BIM (Cao et al., 2017). However, maintaining collaboration among geographically separated members coming from multiple disciplines and organisations in BbCNs has proved problematic (Volk et al., 2014, Liu et al., 2016) and thus worthy of further investigation.

There exists a growing interest in exploring the factors affecting collaboration in BbCNs (Shafiq et al., 2013), yet anecdotal evidence still refers to knowledge gaps in the Body of Knowledge (BOK) on collaboration in BbCNs (Mignone et al., 2016, Alreshidi et al., 2016, Liu et al., 2016). In this context, no explicit BOK has systematically assessed the specific literature on collaboration in BbCNs, but have focused on the extended BIM BOK instead (Zhao, 2017, Santos et al., 2017). This is a major barrier to identifying required directions for research on any topic that might end up in overlooking central aspects and duplication of efforts (Yalcinkaya and Singh, 2015). From a Project Management BOK (PMI, 2013) perspective, this study unravels the contribution of BIM scholarship in the areas of information, coordination and stakeholder management.

With this in mind, conducting systematic review studies to spot gaps and discover core research requirements becomes very relevant (He et al., 2017). This study aims to analyse the scholarship on collaboration on BbCNs. As such, the study maps and analyses the state of existing publications on collaboration on BbCNs. The resulting accumulated knowledge will uncover patterns and relationships between concepts that have remained hidden within the literature on the topic. Besides, the findings will produce evidence to inform, guide and improve future research on the topic. The paper is structured as follows. First, the background and relevant research on collaboration on BbCNs is presented. Next, the relevant research methods to address the research aim are defined. The findings of the study are presented and discussed against relevant literature in the subsequent two sections. Finally, the ensuing section concludes the study by summarising key points and outlining implications for scholarship and practice.

2. Collaboration on construction projects

According to the seminal study by Wood and Gray (1991), "collaboration occurs when a group of autonomous stakeholders of a problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain". Thomson et al. (2009) expounded on the foregoing definition and stated that collaboration requires negotiations among the parties involved to jointly create rules and structures for mutually beneficial relationships. Collaboration is not defined in the same way across different disciplines (Thomson et al., 2009, Bedwell et al., 2012). For management-related fields, collaboration is seen as a relationship structure that follows effective management (Bedwell et al., 2012). This similarly holds for the construction management field as discussed below.

Collaboration that is tightly attached with effective management is deemed a central element of success throughout the entire lifecycle of construction projects (Van Gassel et al., 2014, Suprapto et al., 2015). Collaboration on construction projects is closely linked with communications and seamless share of information among stakeholders (Pryke, 2004, Hughes et al., 2012, Xue et al., 2010, Walker et al., 2017). With the advent of web-based networks and propagation of information technology (IT) into construction activities (Hosseini and Chileshe, 2013), the nature of collaboration has undergone a radical change in recent years (Lee and Yu, 2012, Grilo and Jardim-Goncalves, 2013). In essence, computer-based collaboration has become the norm for contemporary construction projects where team members are scattered across several locations (Niknam and Karshenas, 2015, Solihin et al., 2016) but use a shared database (Lee and Yu, 2012, Hu et al., 2016, Alreshidi et al., 2016). With the rise of BIM as the state-of-the-art technology to foster collaboration (Chen and Hou, 2014, Singh et al., 2011, Solihin et al., 2016), BbCNs have become the centrepiece of collaboration on construction projects (Grilo et al., 2013, Mignone et al., 2016, Liu et al., 2016) as discussed next.

2.1. BIM-based construction networks (BbCNs)

Members of BbCNs typically come from different disciplines, each one with a particular set of skills to enable BbCNs of fulfilling project requirements (Grilo et al., 2013). Yet, success of BbCNs in achieving their goals relies upon members working collaboratively and project data being seamlessly shared across all the organisations involved (Love et al., 2011, Bassanino et al., 2013, Merschbrock, 2012, Kuiper and Holzer, 2013, Lu et al., 2013, Hosseini et al., 2016). As put by Ashcraft (2008), a BIM-enabled project in absence of collaboration means nothing but “scratching the surface”. This has highlighted the crucial role of access to interoperable tools and packages for BbCNs (Grilo and Jardim-Goncalves, 2010, Hu et al., 2016). Besides, the necessity of framing the project environment and shifting common practices to foster collaboration among members in BbCNs has been emphasised

(Merschbrock, 2012, Poirier et al., 2016, Grilo and Jardim-Goncalves, 2010, Alreshidi et al., 2016). Nevertheless, collaboration on construction projects and BbCNs is a multifaceted complex phenomenon manipulated by a wide range of factors (Poirier et al., 2016, Alreshidi et al., 2016). This necessitates looking into the problem with all the antecedents of collaboration included (Merschbrock, 2012, Poirier et al., 2016, Alreshidi et al., 2016).

2.2. Theoretical lens

Research into collaboration has been an active field across a wide range of disciplines and industries over the past decades, which has mobilised agential and social perspectives (Giddens, 1984, Porpora, 2013). The major factors acting as antecedents of collaboration in different industries are similar as asserted in the seminal study by Wood and Gray (1991). As such, several investigators have attempted to define generic antecedents for collaboration to be used across different industries and sectors. As an example, Alreshidi et al. (2016) argued that collaboration antecedents fall within two broad categories being technical factors and socio-organisational ones. The study by Bedwell et al. (2012) discussed that collaboration antecedents are associated with task attributes, the environment, temporal features, structural attributes and entity characteristics with weight of each one in influencing collaboration depending on the settings under question. Moreover, according to the Co-Spaces Collaborative Working Model (CCWM) by Patel et al. (2012), collaboration antecedents are categorised into context, tasks, support, interaction processes, individuals, teams and overarching factors.

Having the context of BbCNs in mind, recently, Poirier et al. (2016) aggregated the findings of noteworthy studies from a wide range of domains and identified five factors termed as *process*, *artefact*, *structure*, *agent* and *context*, by creating a framework for outlining collaboration antecedents for innovative methodologies such as BIM, which enable PM practice.

2.3. Collaboration Pentagon

In this study, drawing upon the framework proposed by Poirier et al. (2016) and the CCWM model proposed by Patel et al. (2012), the collaboration antecedents in BbCNs have been synthesized into a so-called *Collaboration Pentagon* as illustrated in

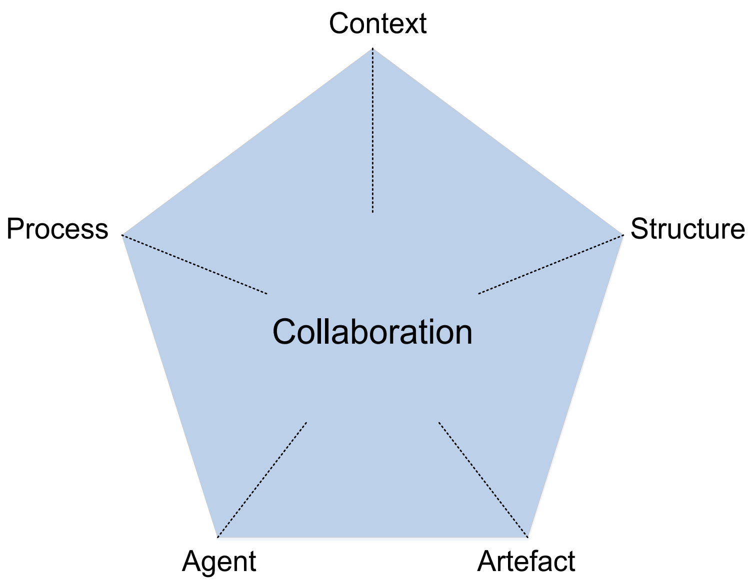

Figure 1. Arguments in support of the synthesis of the *Collaboration Pentagon* are presented next.

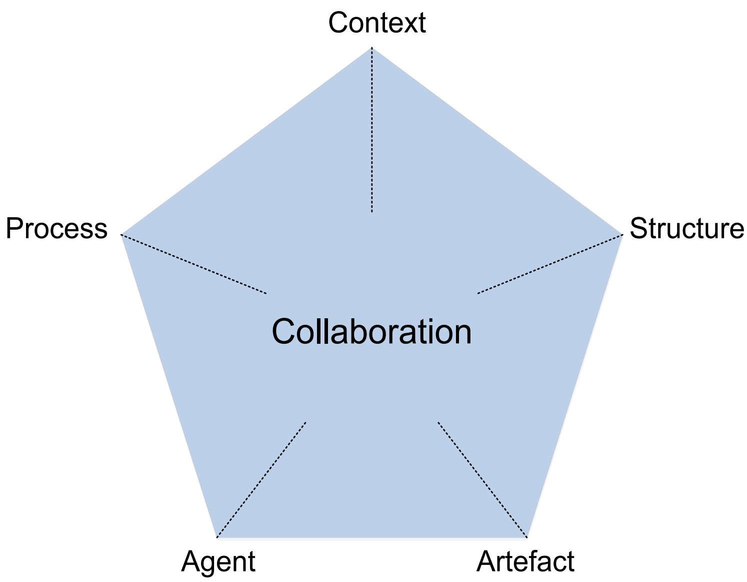

Figure 1. *Collaboration Pentagon*: Theoretical lens of the study

Effective collaboration in BIM-enabled construction projects requires focusing beyond the technology-oriented debate in collaboration (Oraee et al., 2017). In essence, collaborative working requires the integration of all collaboration antecedents (Patel et al., 2012, Bedwell et al., 2012). In other words, collaboration occurs only where all major antecedents to collaboration meaningfully interact with each other (Schöttle et al., 2014, Patel et al., 2012, Hughes et al., 2012, Pryke, 2004, Marheineke et al., 2016). The interaction among these antecedents induces changes in them and the process and eventually prescribes the level or depth of the resulting collaboration (Mignone et al., 2016, Alreshidi et al., 2016). This premise has formed the shape of *Collaboration Pentagon* which synthesizes five interrelated antecedents with reciprocal interactions.

As defined by previous studies (Poirier et al., 2016, Schöttle et al., 2014, Patel et al., 2012), *Artefact* represents the characteristics of the tasks to be completed. *Process* involves attempts through technology supports to convert resources into products and services. *Structure* refers to the common relational system of teams. *Agent* refers to performance of team members in terms of social and interaction activities. As for the *Context*, the factor reflects the specific environment that all these identified antecedents are set within. Accordingly, the *Collaboration Pentagon* in

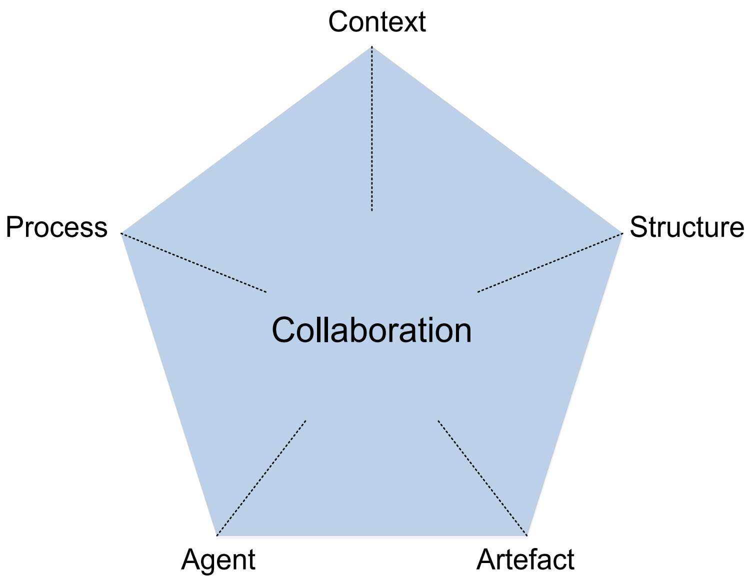

Figure 1 is considered as the theoretical lens of the present study. This provides a yardstick to assess the adequacy of the body of the knowledge on collaboration in BbCNs. In essence,

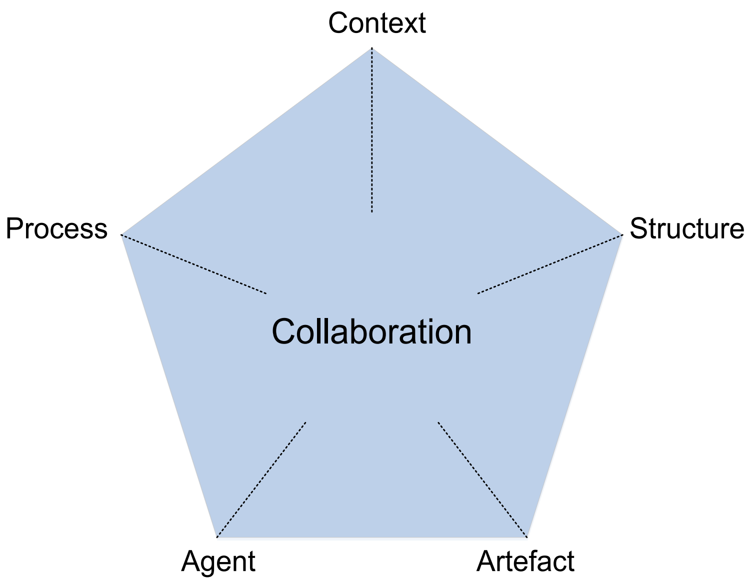

Figure 1 offers a benchmark to show where the gaps lie regarding the antecedents of collaboration and their interactions in the context of BbCNs.

3. Research methods

The primary method utilised in the present study is a “mixed methods systematic review” as termed by Harden and Thomas (2010). Systematic review is the most effective method when a study is focused on flagging up gaps in the body of knowledge and identifying where little research has been done (Petticrew and Roberts, 2008). However, mono-method manual systematic reviews might be biased and prone to problems of subjective judgment and interpretation (Harden and Thomas, 2010, He et al., 2017). This necessitates the use of mixed methods systematic review in synthesising literature on a topic “to enhance the depth and breadth of understanding” (Heyvaert et al., 2016). Mixed methods systematic review studies combine and apply quantitative and qualitative methods for integration and analysis of available literature on a topic (Harden and Thomas, 2010). This needs a protocol to show the methods, the processes and the sampling strategies for data collection to serve the defined objectives of the study (Heyvaert et al., 2016).

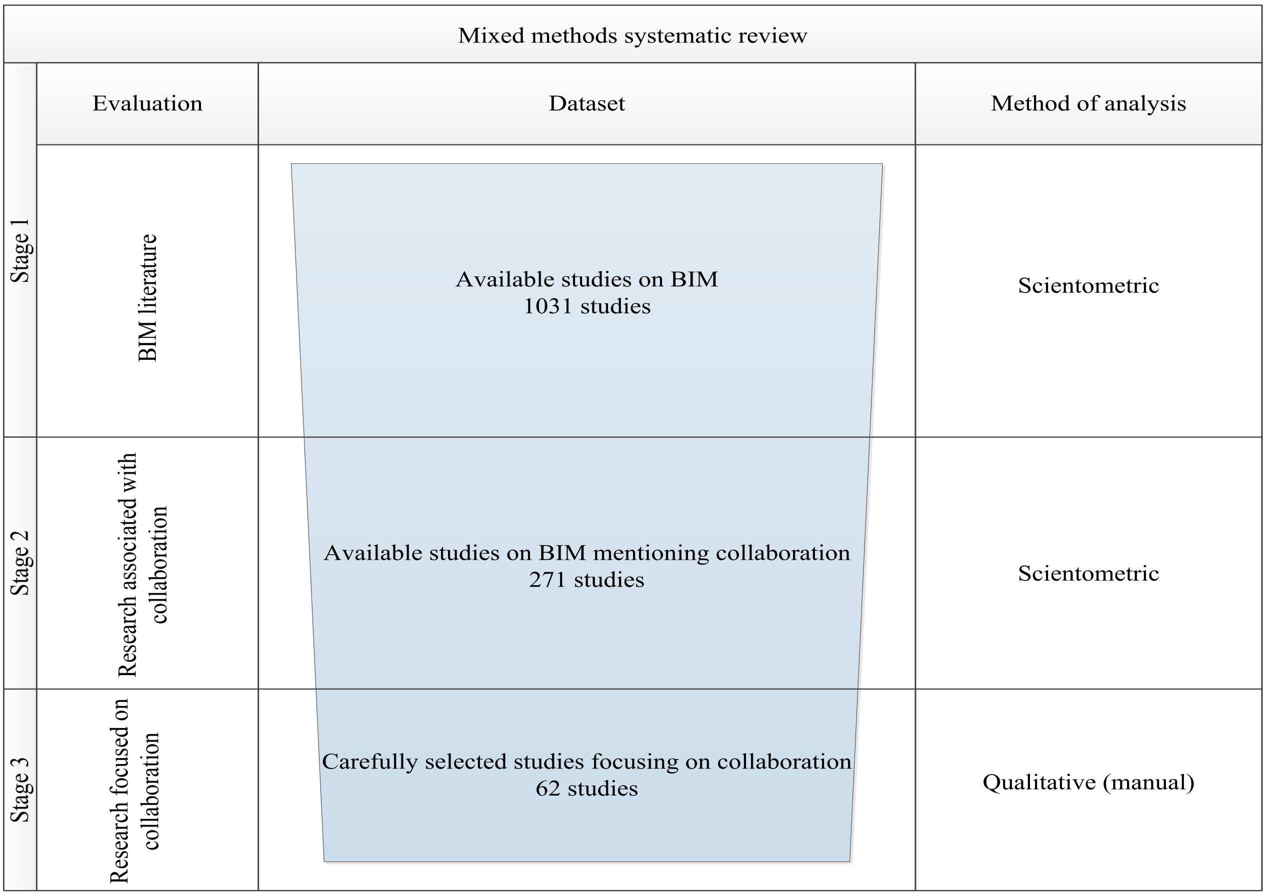

Figure 2. Mixed methods systematic review procedure

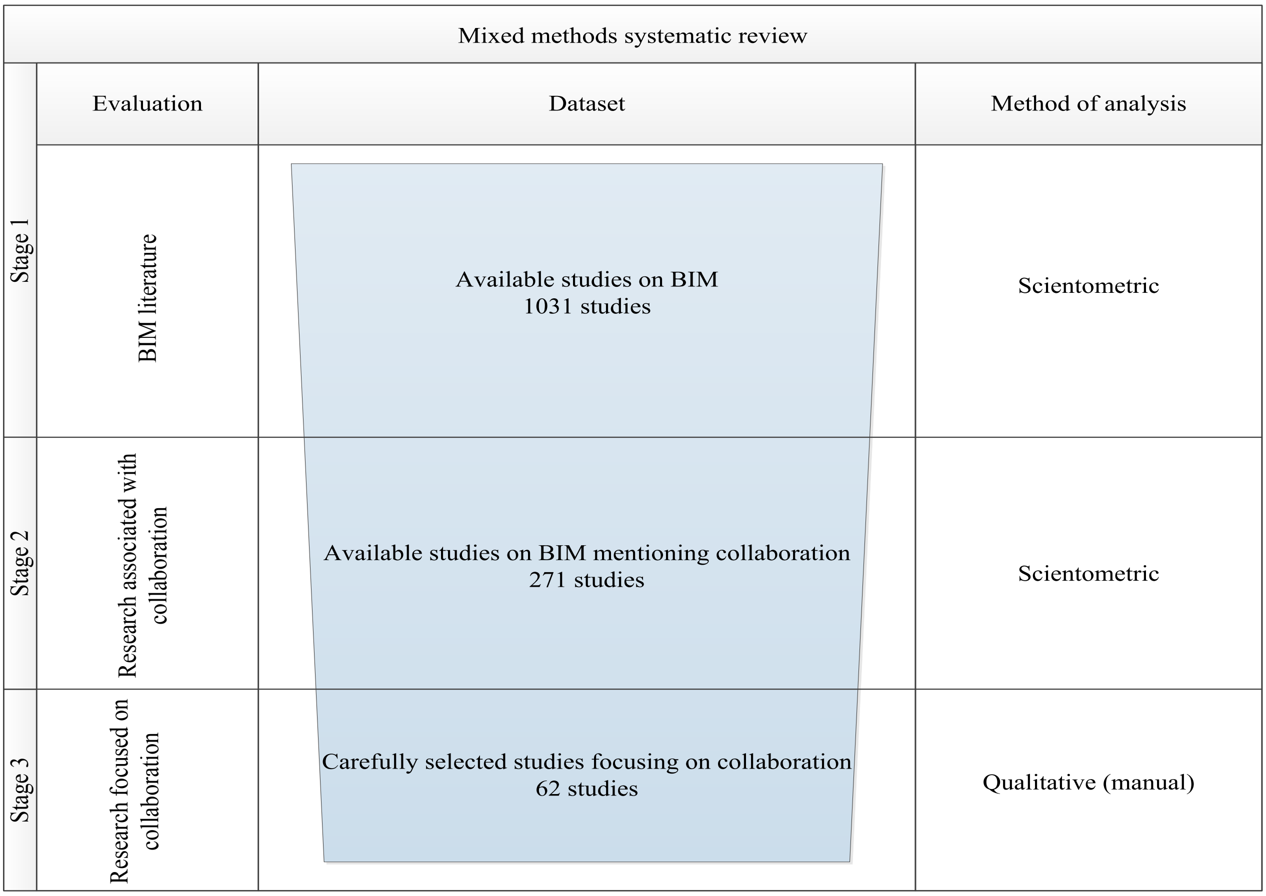

Figure 2 illustrates the protocol followed for conducting a mixed methods systematic review in the present study. The details of the succeeding stages as illustrated in Figure 2 are discussed next.

3.1. Scientometric analysis (stages 1 and 2)

As illustrated in Figure 2, the first and second stages of analysis entail use of scientometric analysis. Manual review of available studies is prone to be biased and limiting in terms of the number of studies to be reviewed by researchers on a topic with a large corpus of literature (He et al., 2017). This has resulted in the emergence of quantified systematic techniques using computer programs to analyse available body of knowledge in an area (Yalcinkaya and Singh, 2015). Of these, scientometric analysis of literature has enjoyed a steady growth in different disciplines. Scientometric analysis refers to mapping and visualisation of a particular large-scale scholarly data set in a knowledge domain (Van Eck and Waltman, 2010). This enables researchers of analysing the intellectual landscape of a research area to fulfil the objectives of their research studies (Cobo et al., 2011). There are a large number of computer programs for scientometric analysis, of which VOSviewer (Van Eck and Waltman, 2010), and Gephi (Bastian et al., 2009) have been utilised in this study. Available tools for scientometric analysis have different capabilities and strengths, thus a thorough analysis of any field necessitates the use of several tools for different types of analysis in one study (Cobo et al., 2011).

Data for scientometric analyses could be extracted from different bibliometric sources such as *Web of Science*, *Scopus*, *EBSCOhost* or *ProQuest*. However, Scopus covers a wider range of journals in the area of construction Project Management (PM) and construction IT than the Web of Science and contains more recent publications compared against other databases (Aghaei Chadegani et al., 2013). The topic of the present study was related to BIM as a relatively new area of literature with studies mostly published in recent years. This justified the use of Scopus as the source for the retrieval of data.

3.2. Qualitative method (stage 3)

The qualitative analysis stage followed the objective proposed by Harden and Thomas (2010) for the qualitative phase of mixed methods systematic review studies. As illustrated in Figure 2, this entailed comparing the concepts, themes and theories outlined in the content of a number of carefully selected studies according to the protocol of the systematic review and the study's *Collaboration Pentagon* theoretical lens. The objective was a qualitative synthesis in which authors do not aim to create new theories but simply try to identify what different studies say and to identify the gaps. This typically occurs through translation of findings across the selected studies into a common language prior to offering any interpretation (Harden and Thomas, 2010). The theoretical lens (*Collaboration Pentagon*) illustrated in

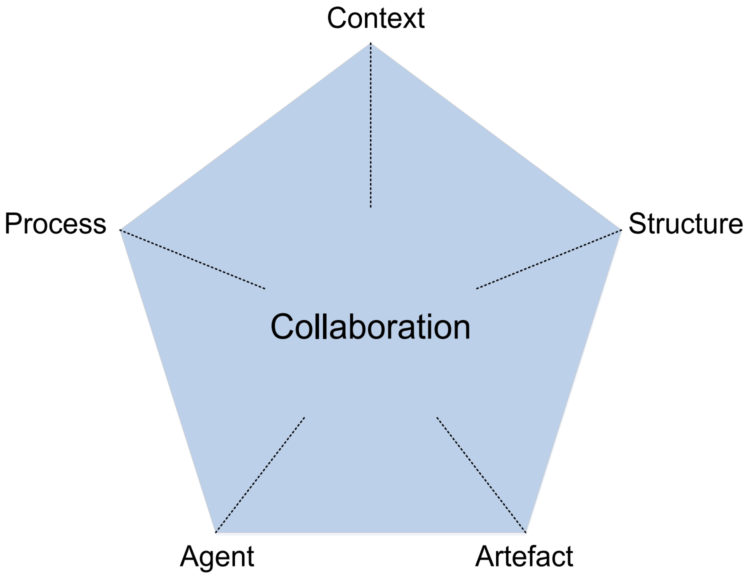

Figure 1, offers the common language in the present study.

4. Findings of the study

4.1. Scientometric analysis

4.1.1. Collaboration within BIM literature (stage 1)

The first stage of the analysis as illustrated in

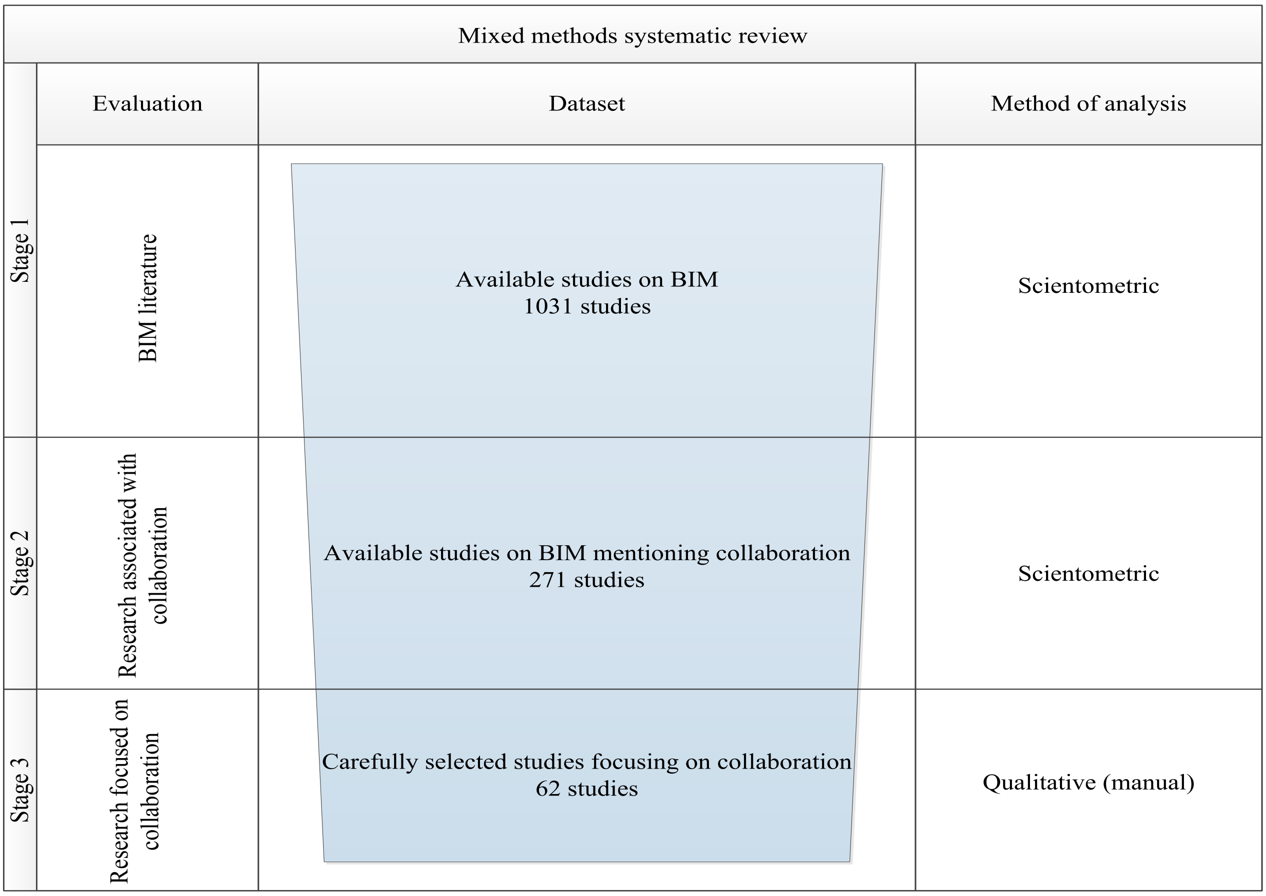

Figure 2, involved retrieval of data on publications on BIM from Scopus. The targeted publications were all article/review studies published in journals (indexed in Scopus) in the last 10 years (2006-2016) having the term *building information modeling* or *building information modelling* in the abstract/title/keywords. The term *BIM* was not used as a search item because it results in inclusion of unrelated studies from other disciplines (Yalcinkaya and Singh, 2015). The preliminary outcome comprised 1031 studies related to BIM methodology in the construction industry as of November 2016.

The data was submitted to *VOSviewer* to create a network of publications based on direct citations. Use of direct citation has become common as a measure to identify the most influential studies in a field of research (van Eck and Waltman, 2014). As recommended by van Eck and Waltman (2014), “fractional counting”, a normalization method, was utilised as the counting method to minimise the impact of sources with a large number of citations on the network. The minimum number of citations for a study was defined as 20, to return a sample of highly influential studies in BIM. Thus, 113 studies met the threshold to be included in the network from which 98 were connected to each other and were used to create the network as illustrated in Figure 3.

VOSviewer creates distance-based maps of networks where the distances among nodes indicate the level of closeness of nodes. The colours of the network demonstrate the concentration of citations with red being the sign of largest citation concentration (van Eck and Waltman, 2014). The font size also differentiates the citation concentration where larger fonts showing higher level of citations for a study. As illustrated in Figure 3, the studies located around the centre of the network were those with large number of direct citations with minimum distance among them. Citation analysis is still a common method for evaluating the influence of studies (Zhao and Strotmann, 2015). Therefore, the centre of network demonstrated the most influential studies which have been the source of information and the point of reference for publications on BIM. These studies were reviewed individually from which none were targeting collaboration in BbCNs. Investigation of this island revealed that included studies are for the most part allocated to applications and implementation of BIM within the industry (Yalcinkaya and Singh, 2015, Merschbrock and Munkvold, 2012). As such, it could be inferred from Figure 3 that none of influential studies in BIM have targeted collaboration. Although collaboration is a key aspect of BIM in construction PM context, it is not among the influential streams of BIM research, and hence it has not yet driven a noteworthy change in BIM scholarship and practice.

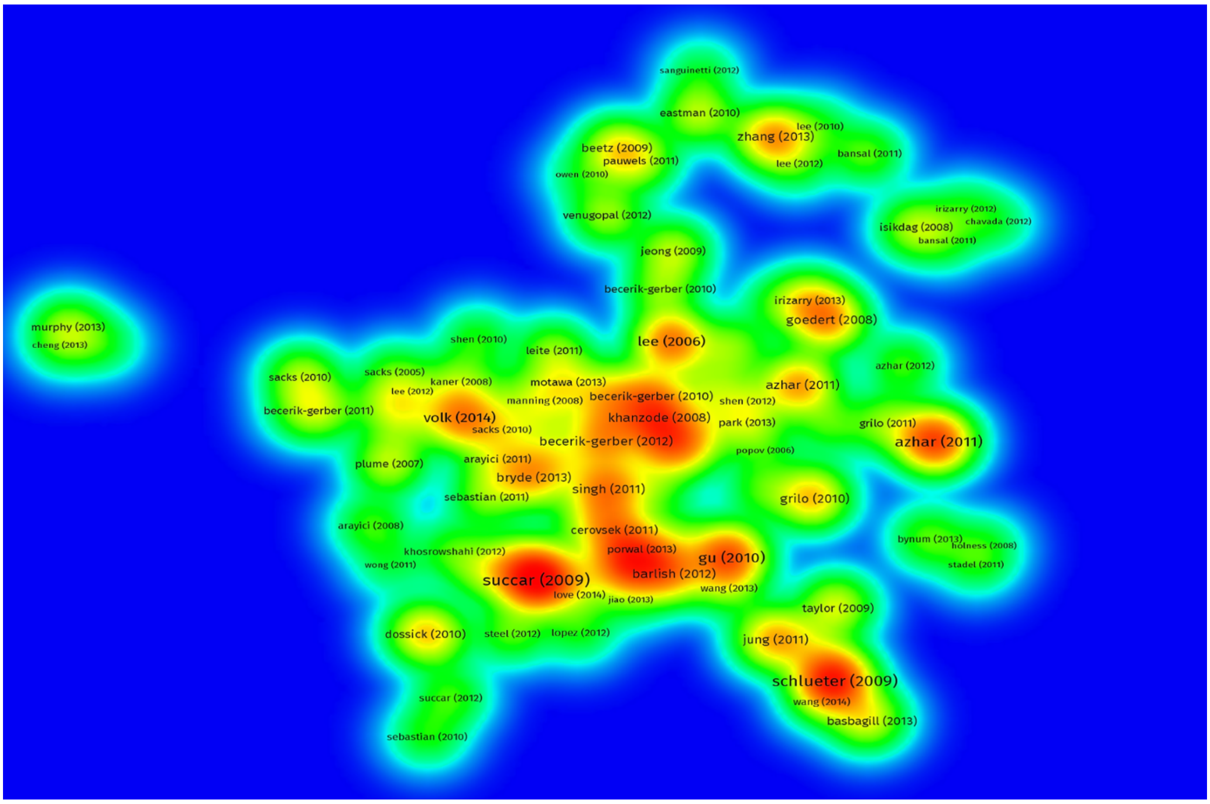

Figure 3. Most influential studies in BIM body of knowledge (density visualization network)

To provide an insightful view, the text-mining ability of VOSviewer was utilised to create a co-occurrence network. VOSviewer deploys the *Apache OpenNLP* toolkit for performing part-of-speech tagging. This function is applicable to the title and abstract of studies included in a dataset (van Eck and Waltman, 2014). "Binary counting" method as recommended by van Eck and Waltman (2014) was applied. This means that in creation of the co-occurrence network, the number of times a noun phrase occurs in the title and abstract of a publication plays no role (van Eck and Waltman, 2014). Out of the 19477 terms identified, 129 terms met the threshold of minimum number of co-occurrence above 40. As the default configuration of VOSviewer, 60% of these terms with the highest relevance were chosen to create the network. This resulted in selection of 77 terms as shown in the co-occurrence network in Figure 4.

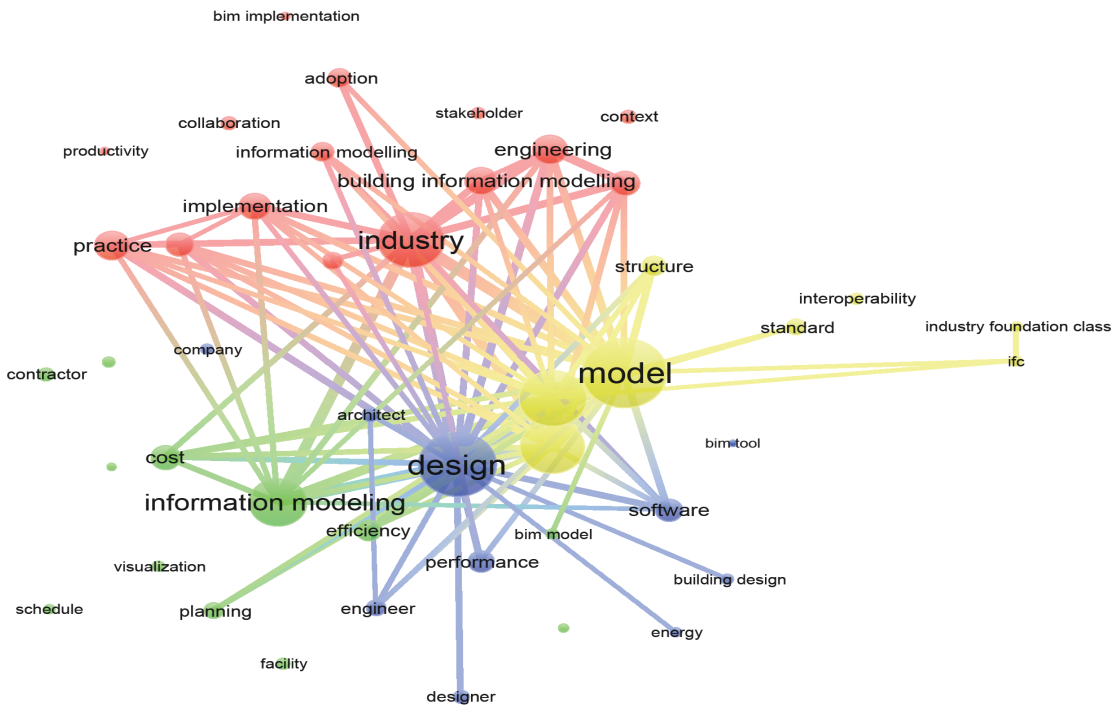

Figure 4. Most co-occurred terms in BIM literature (title and abstract of studies)

The size of nodes on a network differentiates the prominent nodes (Van Eck and Waltman, 2011). As such, collaboration was shown in a size much smaller than prominent terms in the network. This indicates the lack of attention paid to collaboration within the literature on BIM. Hence, the outcome of the text-mining analysis as illustrated in Figure 4 substantiated the fact that compared to other areas of BIM research (see Figure 4), collaboration has received less attention within the existing body of knowledge on BIM. This substantiated the observation in Figure 3.

Furthermore, distance-based networks created by VOSviewer show the relatedness of terms by their distance on the network. Smaller distances between two terms show a stronger relationship between the terms based on their co-occurrences within the published studies (Van Eck and Waltman, 2011). As illustrated in Figure 4, collaboration was found to be a concept being investigated in isolation with no strong connection to other key areas of BIM research. This was an evidence of how exiting scholarship on BIM have overlooked the pivotal role of collaboration in manipulating other areas of BIM research.

4.1.2. Bibliographic mapping of studies associated with collaboration (stage 2)

As illustrated in Figure 2, the second stage of the analysis involved the retrieval of data on publications associated with collaboration within the corpus of academic publications on BIM. The targeted publications were identified by applying the “searching within results” function in Scopus. This search was conducted by applying the term *collaboration* in the abstract/title/keywords of the identified list of studies on BIM (1031 studies). Through limiting the search by use of the *collaboration* term, the number of studies dropped from 1031 to 271 (November 2016). The resultant dataset was downloaded and utilised. This dataset included the collection of 271 studies on BIM that somehow mentioned collaboration on their abstract/title/keywords.

4.1.2.1 Top outlets

The units of analysis (nodes) were defined as *sources* to identify the primary outlets for publishing studies on collaboration in BbCNs. VOSviewer was utilised to extract and create the network of sources out of the created dataset. As discussed, the configurations as recommended by van Eck and Waltman (2014) was deployed. As such, the “type of analysis”, “unit of analysis” and the “counting method” were selected as “citations”, “sources” and “fractional counting” accordingly. A total of 103 sources were identified in the network. With minimum number of citations and documents in a source set to 2 and 1 respectively, 34 sources met these conditions and were included in the network of sources. The network was exported to Gephi for visualisation. That was because, this cooperative procedure results in visualisation of the network in higher quality (Cobo et al., 2011). Gephi 0.9.1 as the latest available version was deployed. Fruchterman and Reingold algorithm was found to be the best in terms of quality and creation of a readable network as illustrated in Figure 5. Fruchterman and Reingold algorithm has a gravity function by which higher values pull the network in toward its centre (Cherven, 2015). The network also shows the flow of information among nodes which in this case could be the flow of citations on papers of the dataset. The size of nodes and the thickness of links show the relative influence of the nodes and the strength of their associations, respectively.

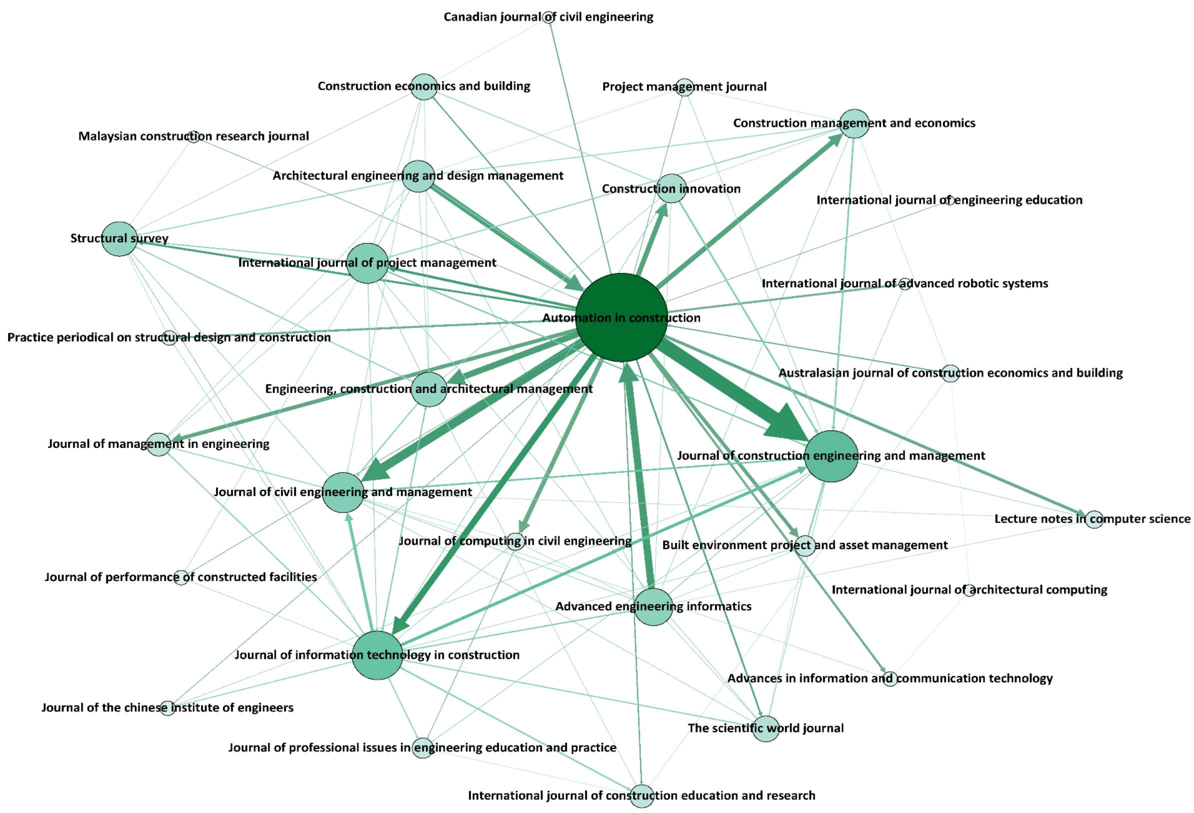

Figure 5. The network of main outlets for publications associated with collaboration in BbCNs

The network as illustrated in Figure 5 shows a clear concentration of highly-cited publications on the topic in "Automation in Construction" which was found to be the most influential outlet on the topic. Judging from the direction of arrows, the flow of information starts from "Automation in Construction" as the source of citations on the topic. The outlets with noteworthy influence on "Automation in Construction" were "Advanced Engineering Informatics" and "Architectural Engineering and Design Management". As per the declared aims and objectives of these three journals, they typically publish studies which are highly technology-oriented with a focus on software, technology, automation and integration process tools and techniques. This points to the fact that influential outlets hitherto have been highly tools/technology-oriented where outlets allocated to management, professional issues, education and construction-related journals have had by far a lower share on influencing BIM research associated with collaboration. As contended by Merschbrock and Munkvold (2012) much of BIM research is driven by the technological imperative perspective.

Therefore, available studies have not targeted managerial and project management features of collaboration due to being focused on tools/technology-oriented capacities of BIM. The findings resonate with observations by He et al. (2017) who argued that BIM is still treated as a technical issue, even in studies allocated to managerial aspects of BIM.

4.1.2.2 Co-occurrence of keywords

To provide an understanding of the contents covered in studies associated with collaboration, a network of keywords co-occurrences was created using VOSviewer based on the dataset containing 271 studies associated with collaboration in BbCNs. “Author keywords” were used instead of all keywords to present a reproducible visualisation of the keywords of studies in the dataset as recommended by Lee and Su (2010). “Fractional counting” was deployed as recommended by van Eck and Waltman (2014). As a result, a total of 830 keywords were extracted from the dataset. With the minimum number of occurrences set to 4, 32 terms connected through 123 links met the criteria to be included in the network. The data were submitted to Gephi for visualisation of the network and duplications in terms were identified. This resulted in having a network of 16 nodes with 51 links connecting them. As asserted by Lee and Su (2010) author keywords show the core of the study and the focal point of an investigation which are carefully selected by the authors. As such, the network as illustrated in Figure 6 presents the top areas of investigation covered by the studies included in the dataset.

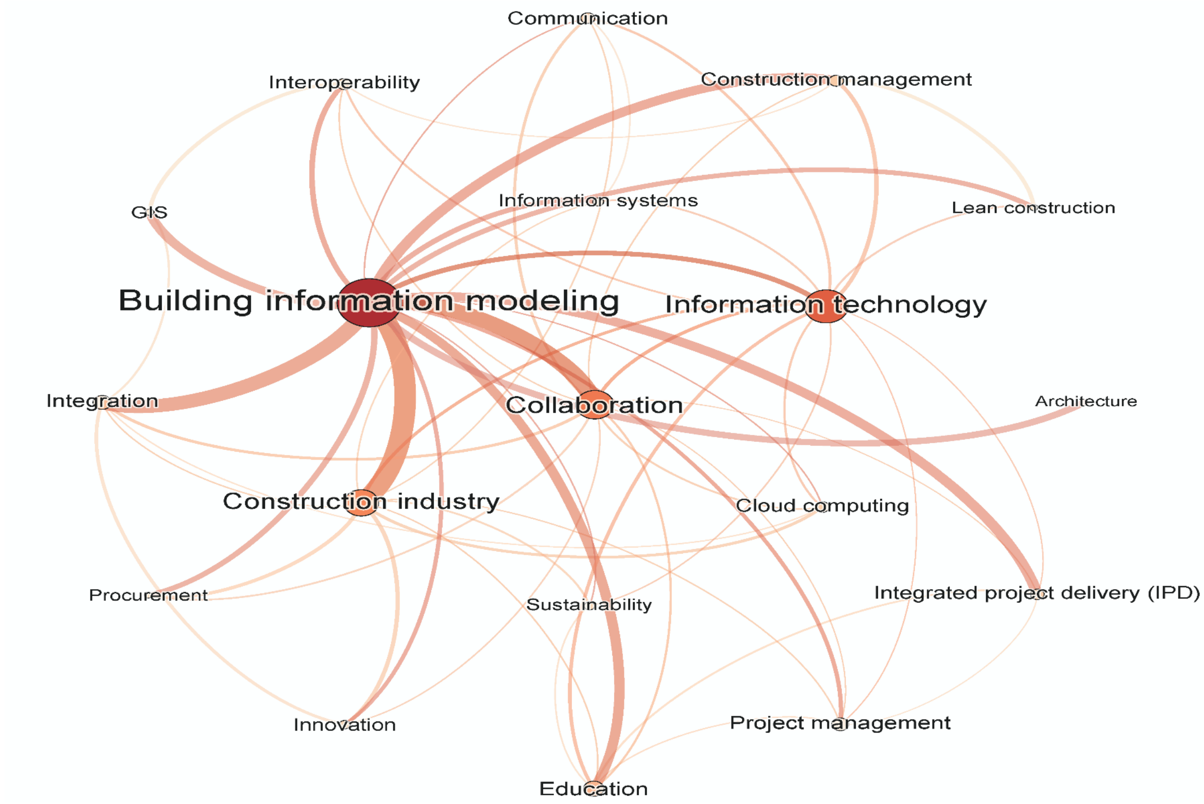

Figure 6. Co-occurrence network of author keywords for the studies associated with collaboration in BbCNs

The PageRank algorithm is a link analysis algorithm which ranks the nodes of a network according to their importance. The algorithm ranks the nodes based on the likelihood of arriving at a node starting from any other node in the network via a non-random graph traversal (Khokhar, 2015). This measure was utilised to rank the nodes in the network, resize and recolour them based on the ranking and identify the most influential ones visually. Collaboration was found to have a fairly strong links with *information technology node* judging from the strength of the link and the distance between these nodes (see Figure 6). The other close neighbour of collaboration was *cloud computing*. This is reflective of the dominant view in the literature. That is, as the findings by Pezeshki and Ivari (2016) exposed, there is a general assumption among BIM research field suggesting that expanding cloud-based BIM is a remedial solution to current problems of collaboration.

As such, the network of co-occurred keywords substantiated the findings observation with regard to outlets. That is, the dominance of technology within the body of knowledge on collaboration in BbCNs is indicated based on the closest keywords to collaboration. Moreover, the findings brought to light that collaboration has been hardly addressed from a PM perspective. This was based on the distance between these nodes on the network and absence of a direct link between the two nodes as illustrated in Figure 6.

4.2. Qualitative phase (stage 3)

In order to narrow down the dataset and identify the studies directly related to the topic, all the 271 identified articles were thoroughly examined by the research team to identify the contents covered by each study. To this end, each study has been examined carefully by at least two members of the research team to identify the relevancy of each study to collaboration in BbCNs, based on the *Collaboration Pentagon* as the theoretical lens in this research study. Final results have been selected upon agreements of all involved team members in examination process on related studies to collaboration in BbCNs. In other words, those studies for which collaboration in BbCNs, following any of the five antecedents of the *Collaboration Pentagon,* was not the focal point were excluded.

As illustrated in Figure 2, upon finalising this examination process, a total of 62 articles as illustrated in Table 1 were identified as the studies focused on collaboration in BbCNs. These comprised carefully selected studies to be analysed in the qualitative phase of the study as illustrated in Figure 2. The full texts of these 62 articles were reviewed and coded. As asserted by Punch (2005), “coding is the starting activity in any sort of qualitative analysis, and the foundation for what comes later”. One well-established method for coding is focusing on comparison, contrast and similarity against an existing framework or model to frame the interpretations (Bazeley, 2013). Such a qualitative analysis shapes and organises the coding system while leaving researchers open to discovery and change. This is through creating a list of a priori codes (Saldana, 2009) and assigning the pieces of information to these codes. The a priori list was based on the *Collaboration Pentagon* as illustrated in

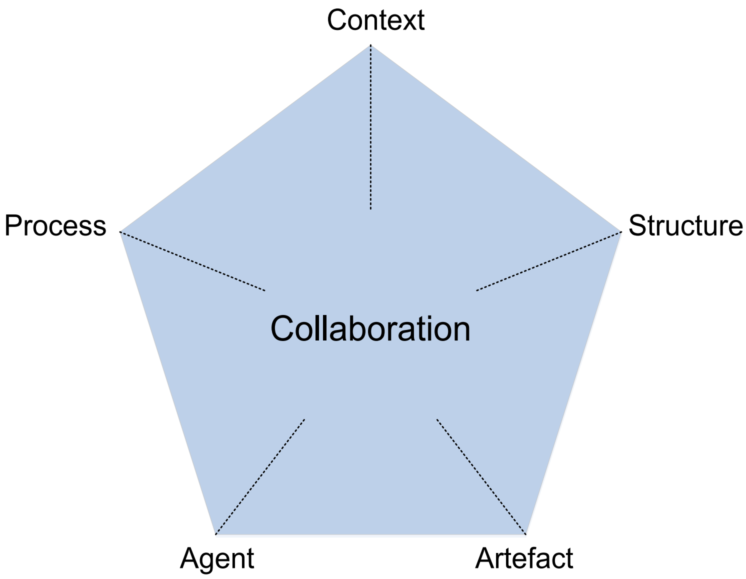

Figure 1. The research team reviewed the full texts of all 62 selected studies and assigned the content to the codes manifested in

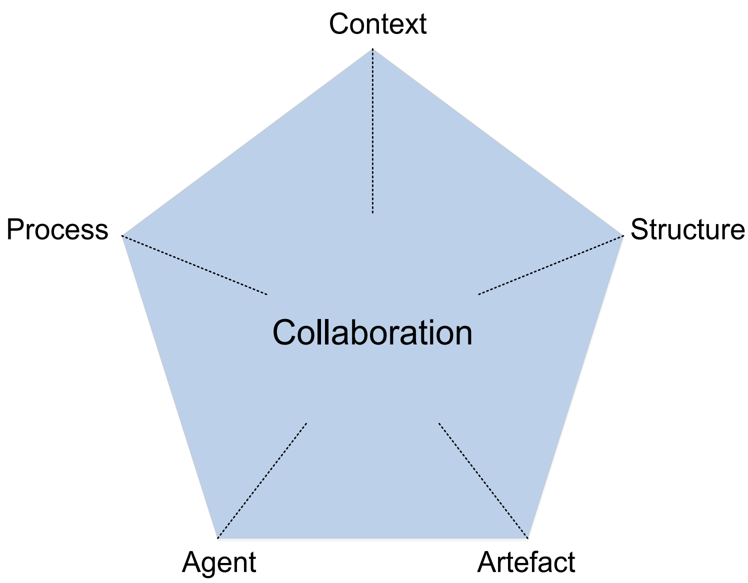

Figure 1. This resulted in categorising the content as illustrated in Table 1, which shows focus of selected studies based on the particular antecedent of collaboration targeted.

Table 1. Studies directly targeting collaboration in BbCNs and the antecedents targeted in each study (see Figure 1 as well)

No	Study	Antecedent of collaboration targeted (*Collaboration Pentagon*)				
		Context	Process	Artefact	Structure	Agent
1	(Abrishami et al., 2014)	•				
2	(Abuelmaatti and Ahmed, 2014)		•			
3	(Adamu et al., 2015)					•
4	(Ahuja et al., 2016)	•	•			
5	(Ajam et al., 2010)		•	•		
6	(Al Mousli and El-Sayegh, 2016)				•	•
7	(Amann and Borrmann, 2016)		•			
8	(Babic et al., 2010)		•			
9	(Bassanino et al., 2013)				•	
10	(Becerik-Gerber et al., 2011)	•	•			
11	(Boton et al., 2013)	•	•			
12	(Chen and Hou, 2014)		•		•	
13	(Chen et al., 2013)	•		•		
14	(Ciribini et al., 2016)		•			
15	(Dossick and Neff, 2010)	•	•		•	
16	(Fernando et al., 2013)	•				
17	(Franz et al., 2017)				•	
18	(Fu et al., 2006)		•			
19	(Goulding et al., 2014)		•			•
20	(Grilo and Jardim-Goncalves, 2013)		•			
21	(Gu and London, 2010)		•			•
22	(Hammad et al., 2016)		•			
23	(Hassan Ibrahim, 2013)		•		•	•
24	(Hu and Zhang, 2011)	•				

25	(Hu et al., 2016)		•			
26	(Isikdag, 2012)		•			
27	(Isikdag and Underwood, 2010)		•			
28	(Underwood and Isikdag, 2011)		•			
29	(Jiao et al., 2013a)		•		•	•
30	(Kent and Becerik-Gerber, 2010)				•	•
31	(Kihong Ku and Mahabaleshwarkar, 2011)	•	•	•		
32	(Kokkonen and Alin, 2016)	•				•
33	(Ku and Pollalis, 2009)	•			•	
34	(Ku K et al., 2008)	•	•		•	
35	(Lee et al., 2015)				•	
36	(Liu et al., 2015)		•	•		
37	(Liu et al., 2016)		•			•
38	(London and Singh, 2013)		•		•	•
39	(Merschbrock, 2012)	•	•			
40	(Mignone et al., 2016)				•	
41	(Niknam and Karshenas, 2015)		•			
42	(Ochieng and Price, 2010)	•				
43	(Olatunji, 2011)	•				
44	(Owen et al., 2010)		•			
45	(Pala et al., 2016)		•			
46	(Papadonikolaki et al., 2016)		•	•	•	•
47	(Park and Kim, 2013)		•			•
48	(Pikas et al., 2013)		•	•		•
49	(Poirier et al., 2016)	•				
50	(Rafiq and Rustell, 2014)		•		•	
51	(Robson et al., 2016)		•		•	
52	(Sackey et al., 2015)	•	•			
53	(Shafiq et al., 2013)	•	•			
54	(Sidawi and Hamza, 2012)		•		•	
55	(Singh et al., 2011)		•			
56	(Solnosky et al., 2014)	•				
57	(Succar, 2009)	•	•			
58	(Van Gassel et al., 2014)			•	•	
59	(Walker, 2016)	•	•			
60	(Imoudu Enegbuma et al., 2014)		•			
61	(Zhou et al., 2014)					•
62	(Zanni et al., 2016)			•		
	Share of targeted antecedent *	37%	68%	11%	27%	21%

Note: The number of studies for each antecedent against the total number of studies focused on collaboration (62)

4.2.1. Context

As illustrated in Table 1, 22 studies (37% of the total studies on collaboration) have focused on the factors falling within the antecedent of "context". The analysis of contents of these studies brought to light that under this category, 2 broad areas have been explored as the potential avenues to enhance collaboration.

- Organisational environment
- BIM education

Studies by Dossick and Neff (2010), Olatunji (2011), Merschbrock (2012), Walker (2016) and Mignone et al. (2016) indicated that the organisational environment surrounding a BbCN, significantly affects collaboration in BbCNs. Alreshidi et al. (2016) acknowledged this premise and termed such as impacts as "socio-organisational aspects". A collaborative BbCNs is a by-product of an environment that supports collaboration (Sackey et al., 2015, Dossick and Neff, 2011). Accordingly, several remedial solutions as below have been suggested in the literature in order to establish such a supportive environment. Within the *Context* antecedent, lack of a legal framework to manipulate the organisational environment and support intra-organisational collaboration was found to be a major barrier to collaboration (Porwal and Hewage, 2013, Alreshidi et al., 2016, Merschbrock and Munkvold, 2015, Rezgui et al., 2013). Ochieng and Price (2010), Dossick and Neff (2011) and recently Liu et al. (2016) and Kokkonen and Alin (2016) highlighted the role of communication styles with regard to organizational BIM-enabled project environments.

In addition to the organisational structure and culture, studies by Succar (2009), Becerik-Gerber et al. (2011) and Pikas et al. (2013) brought to light the importance of including collaboration as a part of BIM education at universities to improve the context as an antecedent of the *Collaboration Pentagon*. According to such studies, BIM educational programs need to be realigned by universities to foster collaboration and train graduates to support a collaborative organisational environment. Skills and knowledge of interdisciplinary collaboration and understanding of work sharing concepts fall within the category of *Context* and are the key skills to be included in BIM training programs and associated university curricula (Wu and Issa, 2013, Abdirad and Dossick, 2016).

4.2.2. Process

As illustrated in Table 1, 42 studies (68% of the reviewed studies) have identified the importance of *Process* on collaboration in BbCNs. These studies have attempted to draw upon the capabilities provided by technology (almost entirely referring to information communication technology) to address the issues of collaboration in BbCNs. The review of the contents showed that these studies have addressed the matter under the two broad categories termed as the items below.

- Tools and software,
- Networks

Seminal studies addressing the topic such as Singh et al. (2011), Underwood and Isikdag (2011), Gu and London (2010) and Succar (2009) put a great emphasis on utilisation of tools and software as a measure to support collaboration in BbCNs. Studies falling this category have suggested a wide spectrum of tools and methodologies in different levels of complexity. Nevertheless, the trend is directing towards use of sophisticated tools such as virtual hands and avatars to create a sense of being there in meetings (Wang et al., 2014a), engaging on-site personnel with BIM-kiosks (Brathen and Moum, 2016) and the use of various methods derived from augmented reality (Gheisari et al., 2016, Wang et al., 2014b, Jiao et al., 2013b).

On the other end of the spectrum, Shafiq et al. (2013) have put emphasis on improving common document management tools as key facilitators of collaboration for BbCNs.

A major part of attempts falling within *Process* antecedent has been on cloud-based tools (Das et al., 2014, Pezeshki and Ivari, 2016, Rezgui et al., 2013). Studies in this area have focused on the availability of reliable networks to facilitate adopting cloud-based systems. Studies by Niknam and Karshenas (2015), Goulding et al. (2014), Grilo and Jardim-Goncalves (2013) and Jiao et al. (2013a) identified that cloud-based platforms have a great potential for integrating models, simulating components and provide seamless sharing of data for end users in BbCNs. Underwood and Isikdag (2011)Underwood and Isikdag (2011) supported such attempts and denoted that a reliable network-based system such as cloud computing and location-free web services are the key facilitators of successful collaboration in BbCNs.

4.2.3. Artefact

As inferred from Table 1, a small fraction of studies on collaboration (11% of the total) have identified the importance of *Artefact* on collaboration in BbCNs. This refers to potential impacts of the task type assigned to a BbCN and how it affects the requirements for establishing collaboration. As examples in this category, studies by Zanni et al. (2016), Liu et al. (2015), Van Gassel et al. (2014) and Ajam et al. (2010) emphasised on the type of tasks that need to be carried out and how task types influence the performance of BbCNs in terms of collaboration.

4.2.4. Structure

Out of the 62 studies illustrated in Table 1, 17 studies (27%) have highlighted the importance of *Structure* antecedent on collaboration in BbCNs. Structure as an antecedent refers to the role of a team configuration and the relational procedures in place, which according to evidence are influential factors on collaboration in BbCNs (Mignone et al., 2016). The best approach for defining different roles and responsibilities (Hassan Ibrahim, 2013, London and Singh, 2013, Ku and Pollalis, 2009) , the design of relationships (Robson et al., 2016) and the best procedure for knowledge sharing (London and Singh, 2013, Mignone et al., 2016, Van Gassel et al., 2014) have been the main areas of investigation under this category.

4.2.5. Agent

The review of studies on the topic showed that 13 studies out of total (21%) have focused on the role of individual team members, that is the *Agent* antecedent, in influencing collaboration in BbCNs (see Table 1). Examples of studies in this category are Gu and London (2010), Kent and Becerik-Gerber (2010), London and Singh (2013) and Hassan Ibrahim (2013). Such studies focus on team members' own set of professional skills, knowledge and experiences alongside their motivation or selection (Papadonikolaki et al., 2016) to collaborate in BbCNs. Focusing on expertise of BIM actors is becoming a new area of research (Pezeshki and Ivari, 2016), yet has remained unexplored with regard to collaboration in BbCNs.

5. Discussion of the findings

Drawing upon the findings of a mixed methods systematic review, several original views and novel insights with regard to available literature on collaboration in BbCNs came to light. The science mapping techniques applied to available studies on BIM showed that collaboration is a core research area addressed within BIM literature (Yalcinkaya and Singh, 2015, He et al., 2017). Yet, compared against its central role in dictating the success of BIM-enabled projects (Mignone et al., 2016), collaboration research has not received the level of attention it deserves. The findings also revealed that collaboration has been almost entirely addressed from a technology-oriented lens. Though BIM is a socio-technical system (Liu et al., 2016), the scholarship on BIM has not addressed collaboration from the standpoint of management and PM, thus scant attention has been paid to people-related features of collaboration in BbCNs. Anecdotal evidence in the literature e.g. (Grilo and Jardim-Goncalves, 2010, Mignone et al., 2016, Merschbrock and Munkvold, 2012, Liu et al., 2016) have referred to such a gap in the body of knowledge on collaboration in BbCNs.

This study makes two main methodological and theoretical contributions in BIM for construction PM. First, the state of collaboration in BIM research is evaluated via scientometric techniques as an objective method which is less error-prone to subjective judgments and bias. Additionally, this study is the first one in its kind which concentrates on systematic assessment of literature on collaboration in BbCNs as the focal point, as opposed to studies that analysed BIM research from technological standpoints ((Zhao, 2017, Santos et al., 2017). Second, current gaps in the literature on collaboration are spotted through a systematic comparison against the *Collaboration Pentagon* (see Section 2.2). The proposed *Collaboration Pentagon* advances our knowledge of collaboration antecedents for BbCNs by highlighting the pivotal role of interactions and emphasising the necessity of considering these antecedents from an all-inclusive perspective. Essentially, this study highlights areas for further exploration of collaboration, such as artefacts, structures and agents, which are currently under-represented in BIM collaboration research. As a result, the study sheds new light on the nature of unexplored areas of BIM collaboration. The outcome of such an assessment reveals how the scholarship has treated the matter from a disjointed and fragmented approach. That is, isolated antecedents have been addressed in different studies without paying attention to the centrality of connections and the synergy among these antecedents. In fact, antecedents of collaboration in BbCNs have been hardly treated as necessary elements of a unified system.

6. Conclusion and Future Research

Fertile grounds for research on collaboration in BbCNs came to the light as the outcome of the present study. These include focusing on general management, PM and social aspects of collaboration in BbCNs. Particular attention is to be paid to investigating the factors associated with *Artefacts*, *Agents* and *Structure* antecedents of collaboration in BbCNs. The findings call for studies that target the impacts of task complexity, task requirements, project type and project objectives and complexity on collaboration in BbCNs. As for the *Agent* dimension, team members' knowledge, skills and abilities and the match between different members in a BbCNs should be taken into account. The gap related to *Structure* warrants further research to identify the best practices for planning the procedure, contractual features and supportive organisational structures where BbCNs are involved. Above all, the main theoretical contribution of the study is the suggestion of the *Collaboration Pentagon* as an inclusive analysis tool for future studies that departs from isolated antecedents of collaboration in BbCNs. Future investigators have to consider the interacting impacts and the synergy among antecedents of collaboration in BbCNs as dispensable elements of the collaboration system for planning their research designs and in turn informing PM practitioners on how to collaborate with BIM.

Despite the contributions of the study as discussed, nonetheless, a number of limitations of this research have to be acknowledge prior to applying the findings. The main limitation concerns the coverage of the study. That is because, with the use of particular keywords, there may be a number of publications that have not been included in the search outcome. Besides, matching and coding the contents of carefully selected studies on collaboration with items of the *Collaboration Pentagon* was a subjective process in nature which is open to different interpretations. In a future study, this could be adverted by incorporating a snowballing referral sampling to increase the credibility of the study. Additionally, scientometric findings are affected by the lack of coverage of certain journals in databases such as WoS. To overcome this, details have been provided for the science mapping procedure to make the research procedure reproducible.

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