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BIM competencies for delivering waste-efficient building projects in a circular economy

Sikiru Abiodun Ganiyu, Lukumon O. Oyedele *, Olugbenga Akinade, Hakeem Owolabi, Lukman Akanbi, Abdulqayum Gbadamosi

Big Data Enterprise and Artificial Intelligence Laboratory (Big-DEAL), Faculty of Business and Law, University of the West of England (UWE) Bristol, Coldharbour Lane, BS16 1QY, Bristol, UK

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A B S T R A C T

Competency measures are increasingly becoming effective ways for construction organizations to measure their ability to deliver waste-efficient projects. Despite the ongoing efforts in achieving the goals of the circular economy through BIM adoption, there is still a paucity of studies on building information modeling (BIM) competencies for delivering waste-efficient building projects. This paper, therefore, aims to identify and investigate critical BIM competencies for delivering waste-efficient building projects in a circular economy. The study adopts a pluralistic approach, using a combination of the review of extant literature, focus group discussions and questionnaire survey. Analysis of the focus group discussion along with the result of the literature review revealed forty-three preliminary BIM competencies, which were subjected to rigorous statistical analyses. Four broad categories of BIM competencies for delivering waste-efficient building projects emerged from the analyses. These are project management-related, construction-related, procurement-related, and design-related BIM competencies. Construction firms could use the BIM competencies identified in this study to enhance the delivery of waste-efficient building projects as well as assess their BIM competency requirements at an individual and organizational level.

1. Introduction

Construction waste has been identified as the most significant contributor to the global landfill (Ibrahim et al., 2010). Globally, the construction industry contributes about 30% of the waste stream, generates about 33% of atmospheric CO2, and consumes over 50% of the natural resources (DEFRA, 2015). In the UK, construction and demolition activities constitute about 44% of the total landfill (DEFRA, 2013). The industry has, therefore, become a major player in driving the global agenda for sustainability with pressure on it to cut down its waste (Yuan, 2013). Consequently, the industry has been prompted to adopt the concept of the circular economy in a bid to reduce the volume of waste generation, preserve natural resources, reduce demand for landfill and improve environmental sustainability. The circular economy agenda, which targets retaining material value in a closed-loop, therefore shows relevance to the construction industry to deliver projects that are waste-efficient and sustainable (Oyedele et al., 2014). The key objectives of the circular economy agenda with regards to the construction industry are to avoid waste at the design stage, minimize waste generation during construction, preserve the quality and value of materials during operation, and ensure reuse or recycling of building components and material at the end-of-life (Peter and Daphne, 2019). Circular economy in the construction industry, in contrast to the traditional linear economy, is, therefore, a restorative and generative system which aims to divert construction and demolition waste from landfills (Reike et al., 2018).

Although innovative technologies, especially building information modeling (BIM), are experiencing rapid diffusion into construction practices (Gholizadeh et al., 2018), however, BIM usage for delivering waste-efficient projects is not commonplace. The principal objective of BIM is to streamline construction efforts through intensified collaborative planning and a clear definition of goals at the early stages of a project (Mihic et al., 2014). As such, BIM is a paradigm shift from the traditional style of working in silos to a collaborative strategy using a digital representation of the building. Several studies have indicated that BIM has enormous potential to stimulate efficient waste management (Bilal et al., 2015; Akinade et al., 2017). Key areas where BIM capabilities could help

* Corresponding author.
E-mail addresses: sikiru.ganiyu@uwe.ac.uk (S.A. Ganiyu), l.oyedele@uwe.ac.uk, Ayolook2001@yahoo.co.uk (L.O. Oyedele), Olugbenga.akinade@uwe.ac.uk (O. Akinade), hakeem.owolabi@uwe.ac.uk (H. Owolabi), lukman.akanbi@uwe.ac.uk (L. Akanbi), abdul.gbadamosi@uwe.ac.uk (A. Gbadamosi).

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in achieving the circular economy in construction include automatic clash detections, design error reduction, an early collaboration of stakeholders, visualization, simulation of waste performances, waste management reporting, among others (Akinade et al., 2018). Despite the steep rise in BIM adoption, the circular economy goal is yet to be attained, and the waste generation within the construction industry keeps increasing (Reike et al., 2018). Wang et al. (2014) indicate that the lack of BIM competencies on the part of practitioners in the construction industry constitutes a significant barrier to the attainment of the circular economy goal, which will ensure waste minimization in the industry. Despite the ongoing efforts in achieving the goals of the circular economy through BIM adoption, there remains no study which has investigated BIM competencies for delivering waste-efficient building projects in a circular economy.

As a result of this gap in knowledge, this study seeks to answer the question: what are the critical BIM competencies for delivering waste-efficient building projects in a circular economy? In answering the research question, the study aims to identify and investigate the critical BIM competencies for delivering waste-efficient building projects in a circular economy. The study seeks to fulfil its aim through the following two objectives:

1. To identify and explore BIM competencies for delivering waste-efficient building projects in a circular economy, and
2. To investigate and unravel the underlined critical BIM competencies for delivering waste-efficient building projects in a circular economy.

A combination of both qualitative and quantitative methods was employed to achieve the above objectives. The study started with a search for relevant literature relating to BIM and construction waste management (CWM) in a circular economy. The essence of the review was to identify a set of preliminary BIM competencies for delivering waste-efficient projects. After that, an exploratory qualitative study was conducted using focus group discussions (FGDs) to verify and validate the preliminary BIM competencies. The FGDs also provided additional BIM competencies for delivering waste-efficient building projects in a circular economy. The identified BIM competencies were then turned into a questionnaire to seek the opinions of construction professionals regarding the level of importance of the BIM competencies in delivering waste-efficient building projects in a circular economy. While objective one was informed by the need to identify BIM competencies for delivering waste-efficient building projects from the literature and FGDs, the motivation for objective two was to unravel the underlined critical BIM competencies for delivering waste-efficient projects using a survey.

The remaining sections of the paper are structured as follow: Section 2 contains a review of the extant literature on BIM competencies for delivering waste-efficient projects in a circular economy. The methodological approach adopted for the study was discussed and justified in section 3, while section 4 presents the data analyses and findings from the study. Section 5 presents a discussion of the four categories of BIM competencies for delivering waste-efficient projects. The last section concludes the paper by highlighting the implications and identifying the limitations of the study as well as areas for further research.

2. A review of BIM competencies and construction Waste Management in a circular economy

2.1. The concept of circular economy

The concept of the circular economy has recently received increasing global attention due to the need to manage finite resources efficiently. The concept of circular economy was widely accepted and promoted by business and governments because it is a solution for reconciling the seemingly conflicting objectives of businesses and environmental sustainability (Ghisellini et al., 2016; Rizos et al., 2017). There are many concepts targeted at addressing the issue of waste management, energy efficiency, greenhouse gas emission and other sustainability issues, which pre-date the term circular economy. These include waste-to-energy supply chain (Pan et al., 2015), eco-industrial park (Zeng et al., 2016), waste-to-resource supply chain, cradle-to-cradle (Braungart et al., 2007), industrial ecology (Garner and Keoleian, 1995), regenerative design (Reed, 2007), product-service-system (Tukker and Tisschener, 2006), blue economy (Pauli, 2010), design-for-deconstruction (Akinade et al., 2017). All these concepts form the basis for what is known as Circular Economy today (Lieder and Rashid, 2016), and the common feature among them is the need to manage resources, minimize waste and protect the environment.

While there are many definitions of a circular economy as documented by Rizos et al. (2017), the one provided by the European Commission (2015) is very succinct and relevant to this study. The EU document described the circular economy as the one that maintains the value of products, materials and resources over their lifecycle and the waste generated are also minimized (European Commission, 2015).

A circular economy has its unique characteristics and requirements that makes it distinct from other forms of economy, especially the traditional linear ecconomy. These characteristics and requirements are well documented in the literature. For example, Laubscher and Marinelli (2014) summarised the key characteristics of a circular economy as: 1. Customer's ability to pay performance or service without ownership, 2. Innovative business models, from transactions to relationship via services and solution models, 3. Reverse cycles that include partners outside current value chains, and 4. Innovations for material-, component-, and product reuse, products designed for disassembly and serviceability.

Similarly, Mendoza et al. (2017) summarised the requirements of a circular economy into four after an extensive review of the classifications of the circular economy frameworks. These requirements are 1. Sustainable business model innovation, 2. Close-loop systems, 3. Product-service systems, and 4. Sustainable product design. The sustainable business model innovation is aimed at significantly reducing the negative impacts of construction wastes on the environment. The close-loop systems consider resource conservation as a key aspect of product design and development while product-service systems are towards selling of service instead of products (goods) as the primary business strategy. However, the sustainable product design requires the development of eco-friendly products and processes through the adoption of three natural principles: waste equals food; use renewable energy; and celebration of diversity (Mendoza et al., 2017). These characteristics and requirements of circular economy are relevant in identifying BIM competencies for delivering waste-efficient building projects. Accordingly, the subsequent subsections will review existing studies on BIM and construction waste management with a view to identify BIM competencies for delivering waste-efficient building projects in a circular economy.

2.2. Systematic review of existing studies on BIM and construction Waste Management

A systematic review of existing studies on BIM and CWM was carried out using Scopus and EBSCOhost as the main search engines based on the functionalities and capabilities of their databases. According to (Yung and Khoo-Lattimore (2017)), Scopus was as the most powerful database among the seven identified databases by Yang et al. (2017) due to its advanced capability, which produced most results. Scopus also serves as a search engine for other databases. EBSCOhost was ranked next to Scopus in terms of their capabilities and search outputs (Yung and Khoo-Lattimore, 2017)

However, to extend the scope of the literature search to enable comprehensive capture of relevant literature for the review, other databases like Science Direct and GScolar were also searched. The search terms used were "BIM" or "Building Information Modeling" AND "Construction Waste Management" OR "Construction Waste Minimization" OR "Construction Waste". The searches were limited to journal articles published in the English language between 2010 and 2020. The initial search of these databases returned 117 and 66 documents for Scopus and EBSCOhost, respectively. Google Scholar and Science Direct also returned 38 and 20 articles, respectively. However, a thorough review of the literature showed that most of the articles returned by Google Scholar and Science Direct have already captured in Scopus and WoS databases. Therefore, retaining these 58 articles will amount to duplication of the literature. In all, a total number of 183 relevant articles were retained for the further systematic review mostly from Scopus and EBSCO.

Despite the prevalence of BIM publications in the literature, only a handful of the papers touched directly on BIM competencies and CWM. Several of the papers focus more on technical BIM requirements for CWM (Cheng et al., 2015; Kim et al., 2017), integrating BIM tools and construction management education (Clevenger et al., 2010; Abbas et al., 2016), stakeholders expectation (Akinade et al., 2018; Ahankoob et al., 2012), and BIM potentials for CWM (Liu et al., 2011; Hamidi et al., 2014). To further refine the search, articles that contained terminologies related to BIM and CWM in their titles, keywords and abstracts were initially selected for review. The search was also limited to only peer-reviewed journal to safeguard the quality of the review and articles not related to BIM competencies and CWM were excluded. A further search through the remaining articles was done to ensure that relevant articles were not left out. The initial searches and refining processes yielded seventeen articles. Additional five articles were retrieved from the initial papers through snowballing. Hence, twenty-two peer-reviewed articles relevant to BIM competencies and CWM were left for the final review and analysis after removing exact duplicates from the searches. Despite considerable efforts to be systematic during the search, selection and the review processes, it is essential to acknowledge the possibility that some relevant articles might have been excluded due to the criteria and the search engines used. However, given the selection criteria and capabilities of the search engines, the selected papers were considered adequate for the review. However, given the selection criteria and capabilities of the search engines, the selected papers were considered adequate for the review.

The selected articles were categorized into three major areas for BIM-based CWM, using content analysis method: 1. Quantification and estimation of CW using BIM; 2. Identification of BIM factors and attributes for CWM; and 3. Development of frameworks for BIM-based CWM. Eleven of the papers under review focused on BIM usage for quantification and estimation of construction waste at different stages of the project lifecycle. Six of the papers discussed the factors and attributes of BIM for CWM, while five of the papers developed frameworks for BIM-based CWM, as shown in Table 1.

Considerable efforts have been made regarding BIM-based quantification and estimation of construction waste in the literature. For example, Won et al. (2016) quantified the amount of waste that can be prevented using a BIM-based design validation approach. Based on two construction projects in South Korea, the study revealed that 4.4–15.2% of construction waste could be prevented using BIM-based design. Miara and Scheer (2019) developed a WasteBIM API to classify buildings based on the quantity of construction waste generated. Akinade and Oyedele, 2019 adopted BIM computational approach to predict construction waste, Lu et al. (2017) explored BIM computational algorithms to manipulate information that can facilitate decision-making for CWM while Guerra et al. (2019) leverage BIM capabilities to develop quantity take-off algorithms of project purchasing records for estimating CW generation.

Regarding the BIM factors and attributes for CWM, Won et al. (2017) identified 23 limitations in the construction and demolition waste management and minimization, which grouped under process, technology and policy categories. On the other hand, Akinade et al. (2018) categorized 22 factors for designing out construction waste into five, including BIM-based collaboration for waste management. Although the papers under this category identified the role of BIM in managing and minimizing construction waste, none of the studies had explicitly identified BIM competencies for managing construction waste.

Various BIM-based frameworks have been proposed in the literature to assess and measure construction waste or to integrate other approaches with BIM for CWM. For instance, Bakchan et al. (2019) developed a multi-dimensional framework (CWM7D) that leverages BIM-based automation to estimate construction waste. Similarly, Liu et al. (2015) proposed an integrated BIM-aided CWM framework (BaW) to address the construction waste during decision-making at the design stage. Marzouk et al. (2019) proposed a framework that relied on BIM and Lean interaction matrix to assess waste during building deconstruction processes.

Analysis of the selected articles also indicated that the papers focused on different strategies for delivering waste-efficient projects. For example, Liu et al.'s (2015) framework addressed the design strategies, Miara and Scheer (2019) developed BIM API to optimize waste at the construction stage while Akinade et al. (2016) identified with commercial and procurement strategies. Gbadamosi et al. (2019) and Jalaei et al. (2019) aligned with material optimization strategies and Won and Cheng (2017) identified BIM opportunities for waste-efficient management throughout the project lifecycle. However, none of the articles explicitly addressed the BIM competence strategies for delivering waste-efficient projects in a circular economy.

Table 1
Classification of selected paper on BIM for CWM.

	Quantification and Estimation of CW using BIM	Identification of BIM Factors and Attributes for CWM	Frameworks for BIM-based CWM
1	Cheng and Ma (2013).	Bilal et al. (2015).	Liu et al. (2015).
2	Won et al. (2016).	Ajayi et al. (2017).	Akinade et al. (2016).
3	Lu et al. (2017).	Salgın et al. (2017).	Wang et al. (2018).
4	Guerra et al. (2019).	Won and Cheng, (2017).	Bakchan et al. (2019).
5	Akinade and Oyedele, 2019	Akinade et al. (2018).	Marzouk et al. (2019).
6	Jalaei et al. (2019).	Li et al. (2020)	
7	Gbadamosi et al. (2019).		
8	Miara and Scheer (2019)		
9	Xu et al. (2019).		
10	Zoghi and Kim (2020).		
11	Guerra et al. (2020).		

2.3. Circular economy and waste-efficiency in construction

Previous researchers have identified the need to deliver projects that are waste-efficient (e.g. Dainty and Brooke, 2004; Ekanayake and Ofori, 2004). Although some earlier studies concentrated on identifying sources and causes of construction waste (Formoso et al., 2002; Koskela, 2004; Lau et al., 2008); subsequent researches have focused on strategies for delivering waste-efficient projects (Yuan and Shen, 2011; Ajayi et al., 2014). Towards this end, different strategies have been proposed to deliver waste-efficient projects within the construction industry. Some studies focused on construction waste minimization strategies through the project lifecycle while other studies were based on waste management strategies - from disposal/landfill through recycling and re-use to reduction strategies (Osmani, 2013; Ajayi et al., 2014).

The literature revealed that the strategies for delivering waste-efficient projects could be categorized under six different groups, as shown in Fig. 1. As pointed out in section 2.2, previous articles have addressed various strategies for CWM except for BIM competence strategies. Accordingly, this paper focuses on BIM competence strategies for delivering waste-efficient projects in line with the growing awareness for the acquisition of relevant skills, knowledge, and competencies by the stakeholders in the construction industry (Hwang and Hg, 2013).

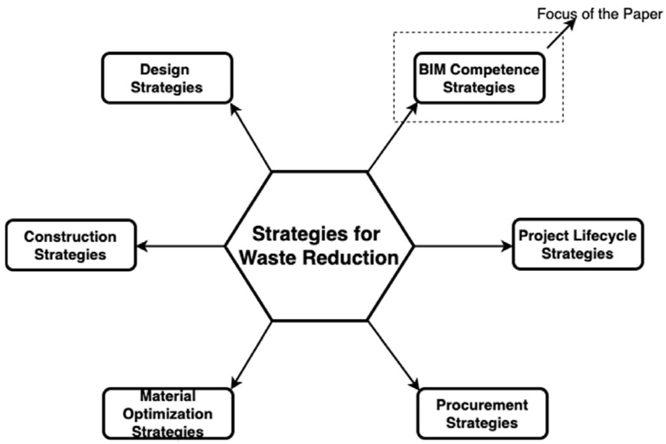

Fig. 1. Framework of strategies for waste-efficient projects.

2.4. Competencies for delivering waste-efficient projects in a circular economy

Competence is a complex concept with many definitions in the literature (Baker and Durrant, 2008). These definitions slightly vary across various industries. In the petroleum industry, competence is the ability to perform certain activities to expected standards (OPITO, 2013). Meanwhile, the health and safety executives' approved code of practice and guidance for gas installations define it as a combination of sets of practical skill, training, knowledge and experience to carry out an installation job and leave it in a safe condition for use. To be competent, individuals must demonstrate sufficient experience, understanding, knowledge, technical skills, and behavior to perform their duties safely over some time, by following relevant procedures and standards.

In the construction industry, a competent person is the one who can demonstrate that they have enough professional or technical training, knowledge, experience and authority to carry out a particular function or duty (Competence in Construction, 2014). In other words, a person is only competent if he can carry out his tasks without supervision and safely deliver his projects to the required standard. Competencies develop over time as individuals practice more on the activities they are performing. Based on the preceding, a BIM competency is the combination of conceptual knowledge, BIM skills (practical knowledge) and experience necessary to perform a BIM-related task (Succar et al., 2012). There are many competencies to be learnt by individual involved in BIM usage within the built environment, depending on their role, discipline, and task. Competencies relate to discipline, specialties, roles, tasks, and levels of practical experience. While some of the competencies could be applied across several disciplines and roles, others are more specific to single discipline and role.

Succar (2010) developed and categorized BIM competencies sets under three sets: technology competency sets; process competency sets, and policy competency sets. Technology competency set includes software, hardware, and network while infrastructure, human resources, products, services and leadership come under process competency sets. Policy competency sets include regulatory, contractual, and preparatory competency sets. The individual BIM competencies are the knowledge, skill and personal traits required to generate model-based deliverables which can be measured against performance standards (BIM ThinkSpace, 2012). Individual BIM competencies can be acquired or improved via education, training and development. Nine different competencies headings were identified under the individual competencies to include: managerial, functional, technical, supportive, administration, operation, implementation, research and development, and core competencies (BIM ThinkSpace, 2012). Succar et al. (2013) proposed an integrated approach to BIM competency assessment, acquisition and application with a focus on individual BIM competencies.

Ajayi et al. (2016) identified the competency-based measures for designing out construction waste. While the study carried out a comprehensive review of the existing waste management strategies and their limitations, it failed to identify the use of BIM as a veritable tool for waste minimization. Ajayi and Oyedele (2018) identified four major critical design factors for minimizing waste in construction projects using a structural equation modeling approach. The identified factors were also limited to the design phase of the building lifecycle. Lu et al. (2017) proposed a computational BIM application for construction waste management using computational BIM algorithms for the manipulation of information to improve decision-making for construction waste management. However, the authors did not identify the critical factors that can support the use of the BIM application for managing construction waste. Akanbi et al. (2018) developed a BIM-based estimator that objectively determines the volume of building materials recovered for reuse and recycling after the useful life of a building. The developed estimator helps demolition engineers to estimate the amount of waste recovered. However, the estimator falls short of meeting the core objectives of a circular economy. Bilal et al. (2015) analyzed the critical feature of BIM software for construction waste minimization using big data. Davies et al. (2015) identified some soft skills required by BIM project teams, while Moustroufas et al. (2015) profiled the essential competency required by software engineers. It is evident from the above analysis of the literature that a gap still exists in identifying BIM competencies for delivering waste-efficient projects.

The discussions on how to reduce the amount of waste being generated within the construction industry is an ongoing debate (Osmani, 2013; Ajayi et al., 2017), going by the fact that the industry is the most significant contributor of waste to landfill sites (Ibrahim et al., 2010). There is a rich volume of literature on various strategies for waste minimization (Jin et al., 2017). The need for the principal actors in the construction industry to be competent (Egbu, 1999) and the types of competencies required to deliver waste-efficient projects have also been identified (Ahadzie et al., 2014; Holtkamp et al., 2015). Some previous researchers (such as Ajayi et al., 2016) have suggested the tasks and textual attributes of competency-based measures for designing out construction waste by designers. However, other authors have identified the critical indicators for assessing the effectiveness of waste management in construction projects (Yuan, 2013). For example, Zhang et al. (2012) identified the key social competencies for construction project managers within the Chinese construction industry. After the review of extant literature, thirty-six competencies for delivering waste-efficient projects were identified as shown in Table 2.

3. Research methodology

A mixed-methods research approach was adopted to achieve the aim and objectives of this study, which requires the use all available resources to explore the research question in order to find answers to the research problem (Morgan, 2007). Mixed methods design allows researchers to combine both qualitative and quantitative data collections and analysis, either concurrently or sequentially (Onwuegbuzie et al., 2010). Accordingly, this study adopted the sequential exploratory mixed methods to collect and analyze data using focus group discussions (FGDs) and NVivo 11, respectively at the first phase. The second phase involved quantitative data collection and analyses using results obtained from the first phase. Questionnaire survey and Statistical Packages for Social Sciences (SPSS) were used for data collection and analyses at the second phase, respectively.

The essence of using sequential mixed methods is to test the results obtained from the first phase by administering a questionnaire survey on broader respondents in the second phase (Oyedele, 2013). Integrating both qualitative and quantitative data in a single study increases the rigor and richness of the research (Denzin and Lincoln, 2009). Fig. 2 shows the methodological flowchart for sequential mixed methods adopted for the study. The next two subsections provide detailed discussions on the two

Table 2
Competencies for delivering waste-efficient construction projects from the literature.

No	Competencies for delivering waste-efficient projects	Reference from the Literature
1	Ability to use visualized (pictorial) model for construction to reduce rework	Osmani et al. (2008); Dainty and Brooke (2004); Baldwin et al. (2007); Ekanayake and Ofori (2004)
2	Knowledge of waste-efficient procurement strategies (e.g. Just-in-Time)	Osmani et al. (2008); WRAP (2009); McKechnie and Brown (2009)
3	Ability to generate different design options based on their likely waste output	Wang et al. (2015); Baldwin et al. (2007); Esin and Cosgun (2007); Formoso et al. (2002)
4	Ability to clearly and adequate define project goals regarding waste	Wang et al. (2014); Baldwin et al. (2007)
5	Ability to identify potential design error	Andi and Minato (2003); Liu et al. (2011); Zhang et al. (2014); Eadie et al. (2013); Al-Hajj and Hamani (2011); Dainty and Brooke (2004)
6	Knowledge of construction activities where reusable materials could be used	Baldwin et al. (2007)
7	Knowledge of interoperability among BIM software for waste management	Oyedele et al. (2013); Al-Hajj and Iskandarani, 2012; Osmani (2013)
8	Automatic capturing of design parameter	Cheng and Ma (2013)
9	Knowledge of integrating deconstructability and reusability techniques into construction	Ekanayake and Ofori (2004); Al-Hajj and Iskandarani (2012)
10	Ability to effectively design for preassembled components	Kozlovska and Splsacova (2013); Formoso et al. (2002)
11	Ability to specify materials directly from models to minimize variation	Muhwezi et al. (2012); Osmani (2013)
12	Knowledge of dimensional coordination	Dainty and Brooke (2004); Marinelli et al. (2014)
13	Proficiency in logistics for material procurement	Al-Hajj and Hamani (2011); Cha et al. (2009)
14	Ability to extract materials directly from models to prevent over/under ordering	Begum et al. (2007); Domingo et al. (2009); Nagapan et al. (2013)
15	Ability to integrating cost-benefit analysis of managing CW into model	Yuan and Shen, 2011
16	Knowledge of how to generate waste-related information from design model	Isikdag and Underwood (2010)
17	Ability to integrate CW into the assessment of construction contractors	Crowther (2005), Davison and Tingley (2011)
18	Knowledge of procurement routes that minimize packaging	Chen et al. (2002); Jaillon et al. (2009); Yuan (2013)
19	Reduced design changes due to accurate information	Tolman (1999); Muhwezi et al. (2012); Zhang et al. (2012)
20	Using volumetric modular design system and principles	Alshboul and Ghazaleh (2014)
21	Knowledge and ability to design for standard materials supplies	Merino et al. (2009); Yeheyis et al. (2013)
22	Optimizing design for standardization of building elements	Del Río Merino et al. (2009)
23	Ability to construct with standard materials generated from the model	Cha et al. (2009)
24	Ability to minimize design changes during construction by adhering to the models	Al-Hajj and Iskandarani, 2012
25	Ability to generate CW related reports from model	Yeheyis et al. (2013)
26	Ability to adopt modular construction techniques	Yuan (2013)
27	Ability to integrate construction process sequencing early	Faniran and Caban (1998)
28	Early collaborative involvement of all stakeholders at design stage	Akinade et al. (2018)
29	Knowledge of using BIM software to support whole-life waste management	Zhang et al. (2014); Eadie et al. (2013)
30	Knowledge of using appropriate BIM software for CW analysis	Zhang et al. (2014); Akinade et al. (2017)
31	Proficiency in engineering capabilities and offsite prefabrication (e.g. 3D printing for prefabrication, etc.)	Faniran and Caban (1998)
32	Ability to increase awareness of resource saving techniques among project stakeholders	Yuan (2013)
33	Ability to initiate adequate communication among and across project teams	Osmani (2013); Domingo et al. (2009); Ganiyu et al. (2017)
34	Ability to use common collaborative platform for information sharing among project stakeholders	Ilozor and Kelly (2011)
35	Knowledge of CW minimization clauses in contract documents	Osmani (2013); Ekanayake and Ofori (2004); Chini and Bruening (2003), Guy and Ciarimboli (2008)
36	Ability and willingness to organize waste management and material handling training for operatives	Wang et al. (2014); Esin and Cosgun (2007); Tam et al. (2000); Ikau et al. (2013); Begum et al. (2007)

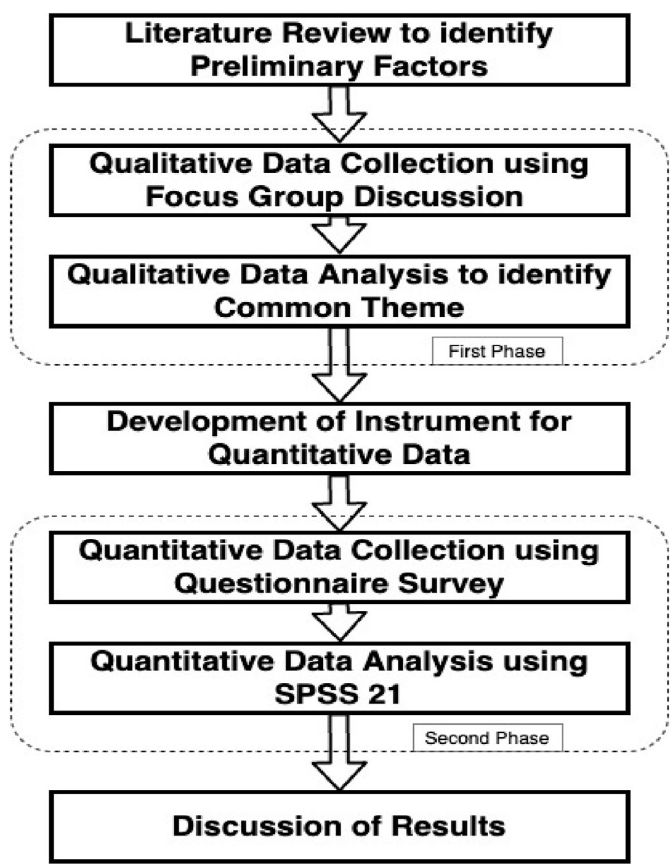

Fig. 2. Methodological flowchart for the study.

phases of the study.

3.1. Qualitative phase of the study

After identifying the preliminary competencies for delivering waste-efficient building projects from the literature, a descriptive interpretative study explored the effectiveness of these competencies to understand the expectations of the participants in terms of BIM competencies for delivering waste-efficient building projects in a circular economy. Creswell (2014) suggested that research participants' experience on the subject matter can be exhumed using a qualitative interpretative method. Two primary forms of data collection methods are common in qualitative research, i.e. interviews and focus group discussions (Moustakas, 1994).

Interview elicits individual participant's perspective of a phenomenon, while FGD involves discussion among a purposely selected group of participants with a shared experience (Nyumba et al., 2018). For this study, FGD was chosen in preference to individual interviews as a method for qualitative data collection to allow participants to build on the responses of one another (Neuman, 2014). The FGD allows for robust discussions and in-depth exploration from different points of view within a short duration (Gray, 2009).

Based on the adopted methodology, five FGDs were conducted with participants selected from the UK construction companies involved in construction waste management works with good knowledge of BIM. Twenty-four (24) professionals were selected based on the suggestion of Polkinghorne (1989) who recommended that FGD participants should not exceed 25. Each of the focus group comprised of an average of five participants with varying level of expertise and experience from the following categories:

1. Architects and design managers
2. Mechanical and electrical engineers
3. Construction project managers
4. Civil and structural engineers
5. Waste contractors and lean practitioners.

In line with the suggestion of Smithson (2000), the composition of each group was drawn from people with a similar background to avoid undue dominant of one professional over the other. The composition allows people with similar experiences to exchange view easily. Table 3 presents an overview of the FGD participants. During the FGD, participants were asked to indicate their willingness to participate in the validation of the research outcome. Ten of the participants expressed their readiness to participate in the validation exercise of the findings of the study.

3.2. Quantitative phase of the study

All the forty-three BIM competency identified from the literature review and FGDs were organized into a questionnaire survey to investigate the criticality of the BIM competencies for delivering waste-efficient building projects in a circular economy. A pilot survey was conducted to test the validity and robustness of the research instrument before the final version is launched (Kraemer et al., 2006). Based on the feedback from the pilot survey, the final questionnaire was refined by removing abbreviations and rephrasing some of the questions for clarity. Participants of the pilot survey should be as close as possible to the targeted population (Van Teijlingen and Hundley, 2001), participants were therefore, randomly selected from the available lists of the professional bodies. The survey link was sent to them via their email addresses. The participants of the pilot survey consisted of four architects, three civil engineers, two BIM managers and two waste contractors, with an average of 10.3 years of experience in the construction industry.

The final questionnaire was designed and launched online, using the Bristol Online Survey (BOS) platform. BOS is a free online platform for designing, distributing and analyzing survey questionnaires. The key advantages of using an online survey include accessibility to remote individuals, save time and cost efficiency (Wright, 2005). Other advantages include the fact that it is quicker to analyze and very convenient. The questionnaire consists of three sections:

1. Cover letter to explain the purpose of the study.
2. General information that captures the particulars of the respondents.
3. Body of the questionnaire, where respondents have to indicate the degree of importance of the BIM competencies on a 4-points Likert scale.

The choice of a 4-Likert scale was to ensure respondents expressed specific opinion that can be useful for statistical analysis without been neutral. The 4-Likert scale ranges from 1 representing 'not important' to 4, which represent 'most important'.

Directories of the five professional bodies in the UK along with the top 100 construction companies served as the sampling frame for the questionnaire. The five professional bodies include 1. Association of Project Managers (APM), 2. Chartered Institute of Architectural Technologist (CAIT); 3. Chartered Institute of Buildings (CIOB); 4. Chartered Institute of Waste Managers (CIWM); and 5. Royal Institute of Chartered Surveyor (RICS). For the final survey, 160 respondents were randomly selected, and the online questionnaire link sent to each of them. After several email reminders, a total number of 121 questionnaires were returned, representing 75.625% of response rate. However, 14 of the questionnaires were removed from further analysis due to incompletion, remaining a total number of 107 useable responses. The useable responses represent 66.875% of the distributed questionnaire, which was considered adequate based on the 30% minimum response rate suggested by Oyedele (2013). Table 4 presents a summary of the distribution of the respondents used for the analysis.

The results from the survey were then subjected to rigorous statistical analysis using reliability analysis, descriptive analysis and exploratory factor analysis. In addition to identifying the importance of each factor from the questionnaire using a significant index rating, factor analysis was also conducted to identify the principal underlying dimensions behind the phenomenon.

4. Data analysis and findings

This section discusses the qualitative and quantitative analyses of the findings from the FGDs and responses from the online questionnaire survey regarding BIM competencies for delivering waste-efficient building construction projects within the UK.

4.1. Qualitative analysis and findings

Data analyses in a descriptive interpretative study follow a structured sequence, which begins with the description of researchers' personal

Table 3
Overview of the focus group participants.

FG	Participants	No of Participants	Range of Years of Experience
1	Architects and design managers	5	12–20
2	Mechanical and electrical engineers	5	9–22
3	Construction project managers	5	12–22
4	Civil and structural engineers	5	8–18
5	Waste contractors and lean practitioners	4	10–16
Total		24	

Table 4
Summary of the distribution of questionnaire respondents.

Professionals	Number distributed	Number of responses	Percentage (%) return	Average yrs. of experience
Project Managers	30	22	73.33	14.2
BIM Managers	25	19	76.00	10.8
Architects	40	26	65.00	14.4
Structural Engineers	25	14	56.00	13.4
Waste contractors	30	20	66.67	10.6
Quantity surveyors	10	6	60.00	12.2
Total	**160**	**107**	**66.875**	**12.6**

experiences with the phenomena. The personal experience is followed by the description of the texts and structures of the discussions through participants' individual experiences (Creswell, 2013). Accordingly, thematic analysis was carried out using an appropriate coding scheme to identify units of meaning from the FGD transcripts and to classify them into recurring themes. The coding scheme helps to identify prevalent issues and concerns across the FGD transcripts, as presented in Table 5.

Besides confirming the importance of the thirty-six preliminary competencies extracted from the literature, the FGDs also highlighted additional seven BIM competencies as shown in Table 6. These competencies include the ability to generate construction waste-related information from the design model, proficiency in waste material classification methods, and knowledge of material science that prevents early replacement of procured materials. Other competencies extracted from the FGDs are the ability to use BIM software to optimize waste management information, ability to use demountable building techniques, ability to make effective CW decisions using models and ability to foster task harmonization among stakeholders to reduce duplication of effort. In all, the total number of forty-three competencies (see Table 6) were compiled for quantitative analyses in the next phase of the study.

4.2. Quantitative analysis and findings

4.2.1. Reliability analysis and significance ranking of each criterion

Reliability analysis was conducted to identify a reliable set of BIM competencies for delivering waste-efficient building projects within the UK construction industry. Using SPSS, Cronbach's alpha (α) reliability coefficient value for the forty-three competencies was 0.916. A reliability coefficient value above 0.7 indicates high internal consistency of the constructs under measurement (Field, 2007). Any item whose value of *'Cronbach's α if item deleted'* (5th column, Table 6) higher than the overall Cronbach alpha of 0.916 should be removed as it does not contribute to the internal consistency of the data (Oyedele, 2013). Based on the result shown in the fifth column of Table 7, three competencies (F4, F8 and F18) whose values are more than 0.916 were deleted from further analysis. The new Cronbach's alpha for the remaining forty competencies rose to 0.920.

After the reliability analysis, the study seeks to find out the significant ranking of each factor. Previous studies (e.g. Tam et al., 2000; Owolabi et al., 2019) have used a similar significant index. The mathematical expression for the significant index is:

Table 5
Sample classification using the coding scheme.

No.	Quotation	Source	Focus Group
1	*"Another way-out could be to* ***optimize the BIM design*** *by keeping in mind the* ***standardization*** *of materials to avoid half-cuts"*	Civil engineer	3
2	*"… We can then extract the types and volume of materials from the BIM model accurately to* ***avoid under/over quotation of materials during procurement****"*	Project manager	3
3	*"Although Just-in-Time delivery could* ***reduce waste generation during construction*** *… if you use Just-in-Time, you will pay multiple transportation fees*	Contractor	5
4	*"…* ***performing optimization using BIM software with little effort****, may provide more opportunities to see that it is commercially viable to reduce waste in all the cases than to generate waste"*	Mechanical engineer	2
5	*"… one of the* ***responsibilities of a competent project manager is to ensure that the client expectations and dream in terms*** *of BIM deliverables are clearly understood and well-articulated to avoid delay and waste"*	Architect	1

Table 6
BIM competency for delivering waste-efficient construction projects from the literature and FDGs.

No	BIM competency for delivering waste-efficient projects	Focus Groups					Reference from the Literature
		1	2	3	4	5	
F1	Ability to use visualized (pictorial) model for construction to reduce rework	✓	✓			✓	Osmani et al. (2008); Dainty and Brooke (2004); Baldwin et al. (2007); Ekanayake and Ofori (2004)
F2	Knowledge of waste-efficient procurement strategies (e.g. Just-in-Time)	✓		✓	✓		Osmani et al. (2008); WRAP (2009); McKechnie and Brown (2009)
F3	Ability to generate different design options based on their likely waste output	✓	✓	✓	✓		Wang et al. (2015); Baldwin et al. (2007); Esin and Cosgun (2007); Formoso et al. (2002)
F4	Ability to clearly and adequate define project goals regarding waste	✓	✓			✓	Wang et al. (2014); Baldwin et al. (2007)
F5	Ability to identify potential design error	✓	✓		✓		Andi and Minato (2003); Liu et al. (2011); Zhang et al. (2014); Eadie et al. (2013); Al-Hajj and Hamani (2011); Dainty and Brooke (2004)
F6	[a]Ability to generate construction waste-related information from design model	✓	✓	✓		✓	FGD
F7	Knowledge of construction activities where reusable materials could be used						Baldwin et al. (2007)
F8	Knowledge of interoperability among BIM software for waste management	✓	✓	✓	✓	✓	Oyedele et al. (2013); Al-Hajj and Iskandarani, 2012; Osmani (2013)
F9	Automatic capturing of design parameter						Cheng and Ma (2013)
F10	Knowledge of integrating deconstructability and reusability techniques into construction						Ekanayake and Ofori (2004); Al-Hajj and Iskandarani (2012)
F11	Ability to effectively design for preassembled components						Kozlovska and Splsacova (2013); Formoso et al. (2002)
F12	Ability to specify materials directly from models to minimize variation						Muhwezi et al. (2012); Osmani (2013)
F13	[a]Proficiency in waste material classification methods	✓	✓	✓	✓		FGD
F14	Knowledge of dimensional coordination			✓	✓	✓	Dainty and Brooke (2004); Marinelli et al. (2014)
F15	Proficiency in logistics for material procurement						Al-Hajj and Hamani (2011); Cha et al. (2009)
F16	Ability to extract materials directly						et al. (2013); Begum et al.

(continued on next page)

Table 6 (*continued*)

No	BIM competency for delivering waste-efficient projects	Focus Groups					Reference from the Literature
		1	2	3	4	5	
	from models to prevent over/under ordering						(2007); Domingo et al. (2009); Nagapan et al. (2013)
F17	Ability to integrating cost-benefit analysis of managing CW into model						Yuan and Shen, 2011
F18	[a]Knowledge of material science that prevent early replacement of procured materials	✓	✓	✓	✓		FGD
F19	Knowledge of how to generate waste-related information from design model						Isikdag and Underwood (2010)
F20	Ability to integrate CW into the assessment of construction contractors	✓			✓	✓	Crowther (2005), Davison and Tingley (2011)
F21	Knowledge of procurement routes that minimize packaging	✓	✓	✓	✓		Chen et al. (2002); Jaillon et al. (2009); Yuan (2013)
F22	Reduced design changes due to accurate information	✓	✓	✓	✓	✓	Tolman (1999); Muhwezi et al. (2012); Zhang et al. (2012)
F23	Using volumetric modular design system and principles	✓		✓	✓	✓	Alshboul and Ghazaleh (2014)
F24	Knowledge and ability to design for standard materials supplies	✓		✓		✓	Merino et al. (2009); Yeheyis et al. (2013)
F25	Optimizing design for standardization of building elements						Del Río Merino et al. (2009)
F26	Ability to construct with standard materials generated from the model						Cha et al. (2009)
F27	Ability to minimize design changes during construction by adhering to the models						Al-Hajj and Iskandarani, 2012
F28	Ability to generate CW related reports from model						Yeheyis et al. (2013)
F29	Ability to adopt modular construction techniques						Yuan (2013)
F30	Ability to integrate construction process sequencing early						Faniran and Caban (1998)
F31	Early collaborative involvement of all stakeholders at design stage	✓	✓	✓	✓		Akinade et al. (2018)
F32	[a]Ability to use BIM software to optimize waste management information	✓	✓	✓		✓	FGD
F33	Knowledge of using BIM software to support whole-life waste management			✓	✓	✓	Zhang et al. (2014); Eadie et al. (2013)
F34	Knowledge of using appropriate BIM software for CW analysis	✓	✓	✓		✓	Zhang et al. (2014); Akinade et al. (2017)
F35	[a]Ability to use demountable building techniques (e.g. collapsible partitions)	✓		✓	✓	✓	FGD
F36	Proficiency in engineering capabilities and offsite prefabrication (e.g. 3D printing for prefabrication, etc.)	✓		✓			Faniran and Caban (1998)
F37	Ability to increase awareness of resource saving techniques among project stakeholders		✓	✓	✓	✓	Yuan (2013)
F38	Ability to initiate adequate communication among and across project teams	✓		✓	✓	✓	Osmani (2013); Domingo et al. (2009); Ganiyu et al. (2017)
F39	[a]Ability to make effective CW decisions using BIM models	✓	✓	✓	✓		FGD
F40	Ability to use common collaborative platform for information sharing among project stakeholders	✓	✓			✓	Ilozor and Kelly (2011)
F41	[a]Ability to foster task harmonization among stakeholders to reduce duplication of effort	✓	✓		✓		FGD
F42	Knowledge of CW minimization clauses in contract documents	✓	✓		✓		Osmani (2013); Ekanayake and Ofori (2004); Chini and Bruening (2003), Guy and Ciarimboli (2008)
F43	Ability and willingness to organize waste management and material handling training for operatives	✓		✓			Wang et al. (2014); Esin and Cosgun (2007); Tam et al. (2000); Ikau et al. (2013); Begum et al. (2007)

[a] = extra BIM competencies identified from the FGDs.

$$Significance\ Index(SI) = \left(\frac{\sum(s)}{NS}\right) \times 100\% \qquad (1)$$

where *s* represents the significant rating on a Likert scale of 1–4, *N* is the number of responses for that particular factor and *S* is the highest significant rating. The significant index and factor ranking are presented in columns 3 and 5, respectively. The top five most significant BIM competencies for delivering waste-efficient construction projects within the UK, based on the analysis, include 1. ability to minimize design changes during construction by adhering to the models, 2. ability to generate construction waste-related information from design model, 3. knowledge of construction activities where reusable materials could be used, 4. ability to use visualized (pictorial) model for construction to reduce rework, and 5. ability to adopt modular construction techniques. Similarly, the least five BIM competencies for delivering waste-efficient

Table 7
Reliability analysis and significance ranking of BIM competencies for delivering waste-efficient projects in a circular economy.

No	BIM competency for delivering waste-efficient projects in a circular economy	Significance Index (%)	Criteria Ranking	Cronbach's α if items deleted
F1	Ability to use visualized (pictorial) model for construction to reduce rework	87.75	4	.915
F2	Knowledge of waste-efficient procurement strategies (e.g. Just-in-Time)	84	26	.916
F3	Ability to generate different design options based on their likely waste output	86.5	8	.916
F4	*Ability to clearly and adequate define project goals regarding waste*	*75.75*	42	*.917*[a]
F5	Ability to identify potential design error	85.25	15	.916
F6	Ability to generate construction waste-related information from design model	88.75	2	.914
F7	Knowledge of construction activities where reusable materials could be used	88.25	3	.915
F8	*Knowledge of interoperability among BIM software for waste management*	*80.5*	37	*.918*[a]
F9	Automatic capturing of design parameter	86.5	8	.914
F10	Knowledge of integrating deconstructability and reusability techniques into construction	82.5	30	.916
F11	Ability to effectively design for preassembled components	85	17	.915
F12	Ability to specify materials directly from models to minimize variation	82.25	31	.912
F13	Proficiency in waste material classification methods	84.25	23	.914
F14	Knowledge of dimensional coordination	85.75	11	.914
F15	Proficiency in logistics for material procurement	85.25	15	.914
F16	Ability to extract materials directly from models to prevent over/under ordering	81.75	33	.915
F17	Ability to integrating cost-benefit analysis of managing CW into model	84.5	22	.916
F18	*Using volumetric modular design system and principles*	*78*	41	*.917*[a]
F19	Knowledge of how to generate waste-related information from design model	83.5	27	.914
F20	Ability to integrate CW into the assessment of construction contractors	85.75	11	.914
F21	Knowledge of procurement routes that minimize packaging	82.25	31	.915
F22	Reduced design changes due to accurate information	83	28	.914
F23	Knowledge of material science that prevent early replacement of procured materials	73.25	43	.915
F24	Knowledge and ability to design for standard materials supplies	84.25	23	.915
F25	Optimizing design for standardization of building elements	85.75	11	.916
F26	Ability to construct with standard materials generated from the model	86.5	8	.914
F27	Ability to minimize design changes during construction by adhering to the models	90	1	.916
F28	Ability to generate CW related reports from model	85	17	. 914
F29	Ability to adopt modular construction techniques	87.75	4	.914
F30	Ability to integrate construction process sequencing early	87.5	6	.915
F31	Early collaborative involvement of all stakeholders at design stage	80.5	37	.914
F32	Ability to use BIM software to optimize waste management information	85.75	11	.913
F33	Knowledge of using BIM software to support whole-life waste management	85	17	.916
F34	Knowledge of using appropriate BIM software for CW analysis	85	17	.915
F35	Ability to use demountable building techniques (e.g. collapsible partitions)	86.75	7	.914
F36	Proficiency in engineering capabilities and offsite prefabrication (e.g. 3D printing for prefabrication, etc.)	84.75	21	.915
F37	Ability to increase awareness of resource saving techniques among project stakeholders	84.25	23	.914
F38	Ability to initiate adequate communication among and across project teams	80.75	35	.913
F39	Ability to make effective CW decisions using BIM models	82.75	29	.912
F40	Ability to use common collaborative platform for information sharing among project stakeholders	79.5	40	.913
F41	Ability to foster task harmonization among stakeholders to reduce duplication of effort	81.5	34	.914
F42	Knowledge of CW minimization clauses in contract documents	80.75	35	.914
F43	Ability and willingness to organize waste management and material handling training for operatives	80.5	37	.914

[a] *denotes competencies whose 'Cronbach's Alpha if item deleted' are above the overall Cronbach's Alpha, which suggest that they could be removed to increase the* overall *reliability*.

construction projects are 1. knowledge of material science that prevent early replacement of procured materials, 2. ability to use common collaborative platform for information sharing among project stakeholders, 3. early collaborative involvement of all stakeholders at the design stage, 4. ability and willingness to organize waste management and material handling training for operatives, and 5. knowledge of CW minimization clauses in contract documents.

4.2.2. Factor analysis

An exploratory factor analysis was carried out in line with the aim of the study, which is to identify and investigate the BIM competencies for delivering waste-efficient projects. Factor analysis involves the use of a statistical technique for data reduction or structure detection. The technique is for observing variability among items or to identify correlated items from smaller variables (Meredith, 1993). Uncorrelated items are detected from the reduced data using the factor analysis. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett test of sphericity values were 0.730 and 0.000, respectively. The two tests confirmed the suitability of the data for factor analysis. For criteria extraction and rotation, principal axis factor and varimax rotation were used, respectively. All competencies with an eigenvalue of 2 and above were extracted for easy interpretation. Furthermore, all criteria with a factor loading of 0.40 and above were selected for grouping the criteria. The analysis shows a four-factor solution with eigenvalues higher than 2 as presented in columns 3 and 5 of Table 8.

Fig. 3 also presented the associated scree plot revealing the graphical representation of the four critical competencies. The four-factor solution was considered as the critical BIM competencies for delivering waste-efficient building projects in the UK, and it accounts for 64.30% of the total variance. The labelling of the critical BIM competencies was in line with the criteria that constitute them based on the inputs from the experts' during the validation exercise. The competencies are as follows:

1. Critical factor 1: Project management-related BIM competencies;
2. Critical factor 2: Construction-related BIM competencies;
3. Critical factor 3: Procurement-relate BIM competencies; and
4. Critical factor 4: Design-related BIM competencies

During the validation exercise, only six out of the ten participants in the FGD that indicated their willingness to participate in the validation of the research outcome were available for the validation. The outcome of the factor analysis was sent to the six available experts for validation of the completeness of the list of BIM competencies and accuracy of the exploratory factor analysis. This process is vital to obtain the experts' opinion on the completeness and accuracy of the factor analysis. The six experts validated the completeness of the BIM competencies, and the validation exercise helps to finetune the naming of the grouping.

5. Discussions

This section discusses findings from the study using quotations from the extracts of FGDs with experts to support results from the questionnaire survey.

5.1. Critical BIM competencies for delivering waste efficient projects in a circular economy

The eigenvalue was used as a measure of grouping the criteria's significance. Based on the eigenvalue, four groups of critical BIM competency for delivering waste-efficient projects in a circular economy emerged from the analysis of the survey questionnaire. Table 8 revealed that two of the critical competencies has higher eigenvalues of 9.99 and 3.17, indicating respondents attached a higher degree of importance to BIM competencies for delivering waste-efficient building projects. The eigenvalues of the other two competencies are 2.43 and 2.13. The four critical competencies are as discussed below.

5.2. Project management-related BIM competencies

The construction industry is project-based. Accordingly, competencies relating to project management were identified as the most critical criteria for measuring BIM competencies for delivering waste-efficient projects, as shown in Table 8 with an eigenvalue of 9.99. In a similar vein, many researchers have identified effective project

Table 8
Factor analysis of BIM competencies for delivering waste-efficient projects in the UK.

No	BIM competencies for delivering waste-efficient building project	Eigenvalue	% variance	Factor loading
	Project management-related BIM competencies	9.99	34.98	
F43	Ability and willingness to organize waste management and material handling training for operatives			.806
F42	Knowledge of CW minimization clauses in contract documents			.756
F39	Ability to make effective CW decisions using BIM models			.658
F41	Ability to foster task harmonization among stakeholders to reduce duplication of effort			.626
F37	Ability to increase awareness of resource saving techniques among project stakeholders			.560
F31	Early collaborative involvement of all stakeholders at design stage			.557
F33	Knowledge of using BIM software to support whole-life waste management			.544
F38	Ability to initiate adequate communication among and across project teams			.541
F12	Ability to specify materials directly from models to minimize variation			.525
F40	Ability to use common collaborative platform for information sharing among project stakeholders			.494
F34	Knowledge of using appropriate BIM software for CW analysis			.470
F32	Ability to use BIM software to optimize waste management information			.465
F30	Ability to integrate construction process sequencing early			.454
	Construction-related BIM competencies	3.17	17.92	
F29	Ability to adopt modular construction techniques			.670
F6	Ability to generate construction waste-related information from a design model			.584
F27	Ability to minimize design changes during construction by adhering to the models			.579
F26	Ability to construct with standard materials generated from the model			.574
F1	Ability to use visualized (pictorial) model for construction to reduce rework			.571
F7	Knowledge of construction activities where reusable materials could be used			.553
F35	Ability to use demountable building techniques (e.g. collapsible partitions)			.551
F28	Ability to generate CW related reports from model			.544
F9	Automatic capturing of design parameter			.462
F36	Proficiency in engineering capabilities and offsite prefabrication (e.g. 3D printing for prefabrication, etc.)			.460
F20	Ability to integrate CW into the assessment of construction contractors			.451
	Procurement-related BIM competencies	2.43	6.06	
F21				.730

(*continued on next page*)

Table 8 (*continued*)

No	BIM competencies for delivering waste-efficient building project	Eigenvalue	% variance	Factor loading
	Knowledge of procurement routes that minimize packaging			
F2	Knowledge of waste-efficient procurement strategies (e.g. Just-in-Time)			.726
F10	Knowledge of integrating deconstructability and reusability techniques into construction			.627
F15	Proficiency in logistics for material procurement			.610
F16	Ability to extract materials directly from models to prevent over/under ordering			.528
F13	Proficiency in waste material classification methods			.444
	Design-related BIM competencies	2.13	5.37	
F3	Ability to generate different design options based on their likely waste output			.566
F25	Optimizing design for standardization of building elements			.515
F14	Knowledge of dimensional coordination			.494
F22	Reduced design changes due to accurate information			.492
F11	Ability to effectively design for preassembled components			.489
F24	Knowledge and ability to design for standard materials supplies			.469
F5	Ability to identify potential design error			.441
Total			64.30	

management as critical to delivering projects (e.g. Chan et al., 2004; Isik et al., 2008). The competency of a project manager regarding BIM is central to the effective delivery of waste-efficient projects. For example, researchers have suggested the following competencies as requirements for a competent project manager: adequate communication (Ganiyu et al., 2017); control mechanism; feedback capabilities; ability to troubleshoot; effective coordination; effective decision making; monitoring; project organization structure; ability to follow plan and schedule and; related previous management experience (Walker and Vines, 2000; Chan et al., 2004). This position reflects the perspectives expressed by some of the participants in the FGDs who submitted that:

> "If a project manager lacks the necessary knowledge and BIM skills of how to deliver waste-efficient projects, he will fail in his responsibilities …. " [Project manager from FG – 3]"

> "… there is the need to employ a project manager who is well-skilled in BIM usage for waste so that we can effectively map out effective waste management strategy … [Contractor from FG – 5]."

In line with the above claims, a competent project manager should be knowledgeable about the construction waste clauses in the contract documents (F42), be able and willing to organize training for operatives regarding waste management and materials handling (F43). Since BIM is regarded as a useful decision-making tool for reducing construction waste (Walker and Vines, 2000; Chan et al., 2004), the ability to make an effective waste-efficient decision using BIM models (F39) ranked high among the project management BIM competencies.

Duplication of efforts due to poor project coordination results in waste of time and material resources. Ability to coordinate and harmonize various tasks among stakeholders (F41) and the involvement of all stakeholders from the beginning (F31) were, therefore, identified as critical project management competencies for delivering waste-efficient projects. The ability of stakeholders to communicate effectively with one another using a BIM platform (F38) is critical to waste minimization (Sebastian, 2001; Ganiyu et al., 2017). BIM is a useful communication tool among all project stakeholders throughout the lifecycle of the project that can be optimized to deliver a waste-efficient project. Buttressing this point, some experts argued in support of a clear flow of information among stakeholders and the need for the project manager to very articulate, thus:

> "… one of the responsibilities of a competent project manager is to ensure that the client expectations and dream in terms of BIM deliverables are clearly understood and well-articulated to avoid delay and waste … [Architect from FG – 1]."

> "Assess to adequate free flow of information from the BIM model by all project stakeholders, as and when due, helps the project team to make informed decisions much earlier and easily thereby saving time and cost … [Manager from FG – 3]."

Additionally, findings from the analysis also revealed the ability to specify material directly from the BIM models as a means of minimizing waste (F12) and the use of a common collaborative platform for sharing information among stakeholders (F40) as critical BIM competencies for delivering waste-efficient projects. The use of BIM software to optimize

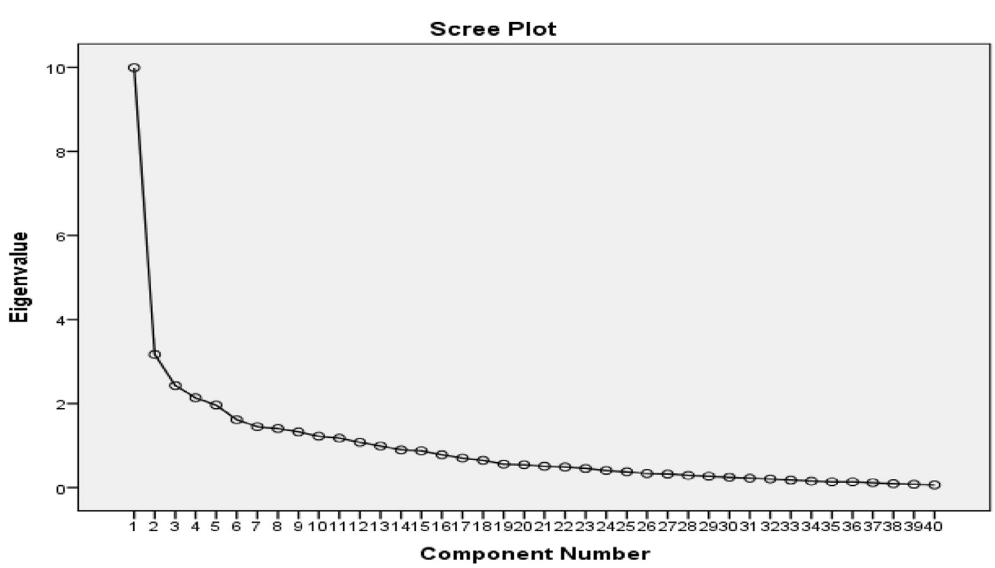

Fig. 3. Scree plot showing the four categories of competencies extracted.

waste management information (F32) and the ability to integrate construction process sequencing early (F30) in the project was also highlighted among the project management-related competencies. Most of the these BIM competencies aligned with the close-loop systems requirements of a circular economy identified by Mendoza et al. (2017).

5.3. Construction-related BIM competencies

Construction phase accounts for most of the wastes generated during the project lifecycle. It is the phase where physical construction takes place from excavation through off-site manufacturing to onsite assemblage of building components. Accordingly, construction-related factor was ranked second in importance based on the result from the analysis, as shown in Table 8 with eigenvalue of 3.17. Given the strategic importance of the construction phase at delivering waste-efficient projects in a circular economy, the result suggests construction-related competencies as the next most critical BIM competency for delivering waste-efficient projects. Some of the major causes of construction waste include the use inappropriate construction techniques such as non-adoption of prefabrication and off-site construction (Tam et al., 2007; Lu and Yuan, 2013), inability to adopt modular construction techniques (Yuan, 2013; Zhang et al., 2012), and lack of early integration of construction processes for waste management, which delays effective decision-making (Yeheyis et al., 2013). Accordingly, participants argued that adopting construction-related BIM competencies could reduce waste generation from the construction stage. Such competencies include the adoption of modular construction techniques using BIM model (F29); ability to generate construction waste-related information from the model (F6); ability to minimize design changes during construction (F27); and knowledge of how to use 3D visualization model to aid construction process and sequence (F1). For instance, all the engineers from FG – 4 and project managers from FG – 3 the agreed that:

> "Modular construction is also becoming part of the industry; it allows coordination of procurement process by utilizing BIM [Civil engineer from FG – 4]"

> "Similarly, offsite construction reduces waste much more than cast-in-situ but … [Project manager from FG- 3]"

Evidence had shown that the offsite construction method and precast materials encourage modular construction, which is very efficient for waste reduction. According to Jaillon et al. (2009), construction waste can be reduced up to 52% using prefabrication construction method. The opinions expressed by the participant corroborated this position. They opined that knowledge regarding reusability of building materials during construction (F7) and the ability to use demountable building techniques (F35) could help deliver waste-efficient projects. Parametric modeling and visualization are required for intelligent modeling of buildings. These features aid the understanding of all the stakeholders and ease BIM adoption across the construction industry to improve project delivery and building performance (Tolman, 1999). One of the participants from the FGD argued:

> "… assembly of building elements using visualization of BIM model enhances easy constructability and ability to place fittings accurately. [Electrical engineer from FG – 2]."

Deconstruction refers to the ability to disassemble wholly or partially a building to facilitates component reuse and material recycling (Kibert, 2008) to eliminate demolition through the recovery of reusable materials (Gorgolewiki, 2006). Deconstruction differs from demolition in that while the former involves the careful dismantling of the building components in such a way that large proportion of the materials and components supports reuse and recycling, the latter usually lacks consideration for primary reuse of the building components. During the FGD, participants emphasized the need to integrate deconstruction and reusable techniques to BIM models.

The findings from the FGDs also reinforce the assertion that the ability to integrate deconstructability and reusable techniques to BIM model determines the competency for delivering waste-efficient projects as stressed by Yeheyis et al. (2013). Adequate planning for the buildings' end-of-life would ensure that a significant proportion of the materials and components are reused, thereby diverting a substantial portion of demolition waste from landfill. This submission conforms with the products design for disassembly and serviceability charactrictics of a circular economy of Laubsche and Marinelli (2014).

5.4. Procurement-related BIM competencies

Another group of critical competencies, according to the survey results, are the procurement-related BIM competencies. This set of competencies were ranked third with an eigenvalue of 2.43, as presented in Table 8. Procurement involves all the processes needed to deliver construction materials to site on time and in safe conditions. According to Dissanayaka and Kumaraswamy (1999), the scope of procurement refers to the framework within which construction is brought about, acquired, or obtained. It is a crucial stage for waste management planning in construction projects. Formoso et al. (2002) identified several causes of construction waste relating to procurement such as packaging materials, double handling, and improper materials storage. There are different strategies to ensure waste-efficient procurement process within the construction industry. Among these are Just-in-Time (JIT) strategy that ensures delivery of construction materials to site in batches based on need (Ballard and Howell, 1997); improved collaboration among the supply chains (Oyedele et al., 2013); avoidance of materials over-ordering, and reduced material packaging (Dainty and Brooke, 2004).

In line with the sustainable business model of a circular economy of Mendoza et al. (2017), there was a consensus among participants that BIM competencies could mitigate the causes of construction waste due to procurement. Procurement-related BIM competencies identified include knowledge of procurement routes that minimize packaging (F21); knowledge of waste-efficient procurement strategies e.g. JIT (F2); adherence to material specification documents from BIM model for procurement; and knowledge of integrating deconstructability and reusability techniques into construction (F10). FGD participants summed up these perspectives, thus:

> "… Just-in-time approach, where only the required materials from BIM models are procured to generate lesser waste … [Project manager from FG – 3]"

> "… We can then extract the types and volume of materials from the BIM model accurately to avoid under/over quotation of materials [Project manager from FG – 3]"

These excerpts show that automatic generation of materials specification from BIM models could minimize variation during procurement. JIT strategy introduced by Toyota in 1987 has been adopted and applied to the construction industry in various forms (Ballard and Howell, 1997). The essence of JIT is to ensure that construction materials are delivered to sites only when, and in the quantities needed. In a similar vein, efficient material take-off from the BIM model (F15) prevents over/under-procurement of materials, which often results to waste (Nagapan et al., 2013). Muhwezi et al. (2012) submitted that adherence to material specification documents from BIM models for procurement eliminates unnecessary variation and helps deliver waste-efficient projects by grouping similar waste material together for easy recycling and reuse.

Participants equally argued that proficiency in material procurement logistics (F15) and waste material classification methods (F13) could help reduce the length of time the materials are stored. Similarly, efficient material procurement eliminates over-ordering and double handling that could result in breakages. Pull system, a process for delivering materials on a minimum-maximum inventory basis could help save transportation cost and reduce environmental pollution.

5.5. Design-related BIM competencies

Design-related BIM competencies ranked fourth with an eigenvalue of 2.13, as indicated in Table 8. As an interactive process, the design phase consists of three key stages, according to the RIBA program of work(-RIBA, 2013) (i. e. conceptual, developed, and technical design stages). These design stages help to refine design workflow, software requirements, and to generate design documents and models such as building drawings, material specifications, BIM models, schedule of work, and bill of quantities. Evidence from extant literature on sources of construction waste suggests that design stages account for a significant proportion of construction waste (Poon, 2007; Yu and Jaillon, 2004; Oyedele et al., 2013). The leading causes of construction waste at the design phase includes the inability to generate different design options, inability to identify potential design errors that could lead to design changes (Poon, 2007; Osmani et al., 2008), unfamiliarity with material alternatives during the design (Ekanayake and Ofori, 2000), lack of knowledge about standard sizes of materials, and poor dimensional coordination (Treloar et al., 2003).

Participants in the FGDs argued that BIM could help overcome the causes of construction waste through appropriate design competencies. Design-related BIM competencies from the survey results include the ability to generate different design options based on waste output (F3), optimizing design for standardization of building elements (F25) and knowledge of BIM for dimensional coordination (F14). The knowledge of dimensional coordination is needed for space planning and component fitting to ensure that all the components fit together without the need for offcuts (Trikha, 1999). Supporting this view, some of the participants of the FGDs affirmed that:

> "… you know it is possible to generate many design options using BIM tools that could be used to create different alternatives of waste-efficient building … [Lean practitioner from FGD – 5]"

> "… most of the construction and design waste is due to changes in the design, lack of BIM knowledge for dimensional coordination, and standardization of materials … [Architect from FGD – 1]"

The above quotes suggest that the knowledge of dimensional coordination is essential in reducing construction waste. Similarly, optimization of BIM design for standardization of building elements favors construction waste reduction (McKechnie and Brown, 2009; WRAP, 2009) while material standardization encourages mass production of components and enables easier identification of components during reuse (Osmani et al., 2008). Modular design system encourages repetition of components using efficient metrication to reduce dimensional variability and construction waste (Esin and Cosgun, 2007; Wang et al., 2010). Accordingly, some of the participants argued that:

> "Another way-out could be to optimize the BIM design by keeping in mind the standardization of materials to avoid half-cuts … [Civil engineer from FGD - 3]"

> "Yes, certain design solution would inherently produce more waste … some are likely to generate more waste than modular design and requires more time to build it. [Design manager from FG – 1]"

Other design-related BIM competency for delivering waste-efficient projects from the survey findings include the ability to reduce changes due to accurate information from the model (F22), ability to design for preassembled components and standard materials effectively (F11 & F24), and ability to identify potential errors (F5). Thus, results of the study agreed with earlier findings that BIM could be utilized to design out waste instead of concentrating on managing the waste after its generation (e.g. Ajayi et al., 2017; Yuan, 2013). This ability of BIM will ensure effective management of construction waste right from the planning stages, through subsequent stages, i.e. design, construction, commission, usage, and maintenance stages, to the end of life. This whole lifecycle consideration fits to the close-loop systems requiremnents of a circular economy. As such, integration of existing tools with BIM would offer greater flexibility to influence the cost and performance of buildings at a stage where the design change is relatively cheaper.

6. Summary and conclusion

6.1. Implications of the study

Research findings of this study present significant implications for BIM practices in particular and building construction industry in general. To deliver waste-efficient buildings, professionals in the construction industry need to be BIM competent since the UK government has directed the use of BIM on all publicly procured projects. Hence, BIM specialists need to continuously update and upgrade their knowledge and skill through education and training in the form of continuous professional development programs. Findings from the study imply that BIM specialists in the construction industry must be proficient not only in the technical application of BIM software tools for designing and creating visual models but must also be competent about how to use BIM collaboratively for delivering waste-efficient projects. Apart from the general knowledge of BIM tools, competencies must be developed across the four critical categories of BIM competencies identified in this study to deliver waste-efficient building projects in a circular economy.

Another significant contribution of the study to the concept of circular economy in the built environment is that the critical factors identified could provide a basis for measuring and evaluating individual and organizational competencies for delivering waste-efficient projects on BIM-enabled projects. Based on the continuous competence development theory (Murray and Chapman, 2003), which focuses on how to improve organizational performance through sustainable incremental innovation, the identified critical factors can also be used by construction organizations interested in leveraging BIM competencies for delivering waste-efficient projects to assess the knowledge, skill, and training needs of their BIM specialists. Though it appears that it is the responsibility of an organization to empower their BIM specialists with the appropriate competencies to perform their responsibilities, however, the critical factors identified in this study can be used by individuals to measure their employability and competitiveness.

6.2. Conclusion

Construction waste is a major environmental challenge with significant contribution to landfill. To attain the goal of a circular economy within the construction industry, various CWM strategies aiming to reduce construction waste to the barest minimum have been proposed. Given the wide adoption of BIM within the UK construction industry, this study examined the critical BIM competencies for delivering waste-efficient projects in a circular economy. The study adopted sequential exploratory mixed methods to investigate the research aim and objectives. Forty-three BIM competencies that could help deliver waste-efficient building projects in a circular economy were identified from the qualitative analyses at the first phase of the study. The identified BIM competencies were developed into a questionnaire survey and the resulting data subjected to exploratory factor analysis to determine their degree of importance in delivering waste-efficient building projects.

The result of the analyses revealed four categories of BIM competencies that are critical for delivering waste-efficient building projects in a circular economy. These categories are project-management-related, construction-related, procurement-related and design-related BIM competencies. Analyses of the findings further showed that thirteen of the BIM competencies are related to project management while eleven BIM competencies converged under construction-related competencies.

Procurement-related BIM competencies contained six different competencies while seven competencies are related to design BIM competencies. In all, thirty-seven BIM competencies were considered critical for delivering waste-efficient building projects within the UK construction industry.

Findings of the study also revealed that the five highest-ranked BIM competencies for delivering waste-efficient projects within the UK construction industry are: the ability to minimize design changes during construction by adhering to the models (F27); ability to generate construction waste-related information from design model (F6); knowledge of construction activities where reusable materials could be used (F7); ability to use visualized (pictorial) model for construction to reduce rework (F1) and; and ability to adopt modular construction techniques (F29). On the other hand, knowledge of material science that prevents early replacement of procured materials (F23); ability to use common collaborative platform for information sharing among project stakeholders (F40); early collaborative involvement of all stakeholders at the design stage (F37); ability and willingness to organize waste management and material handling training for operatives (F43); and knowledge of CW minimization clauses in contract documents (F42) were considered as the five lowest-ranked BIM competencies.

It is expected that the factors with the highest Eigenvalue will produce most of the top competencies (Hayton et al., 2004). However, it is interesting to note that all the top five BIM competencies are construction-related with the second-highest Eigenvalue. While evidence shows that design, procurement, project management and construction have huge impacts on waste generation, it is not entirely clear why the project management-related BIM competencies were not captured as part of the top five competencies, despite its highest Eigenvalue. However, this may be so because the circular economy in construction is generally associated with physical waste generated during onsite construction activities (Esa et al., 2016).

6.3. Limitations and areas of further studies

Despite the contributions of the study, it has some limitations. The fact that all participants are from the UK only imposed a limitation to countries where the findings of the study can be applied. However, given the level of awareness of BIM and circular economy in the UK and the expertise of the participants, findings from this study are essential in breaking new frontiers with regards to strategies for delivering waste-efficient building projects. On this note, it is suggested that future studies may wish to test the applicability of the identified BIM competencies for delivering waste-efficient building projects in other countries or across different countries.

Despite this limitation, this study has successfully identified and investigated, for the first time, a set of critical BIM competencies for delivering waste-efficient building projects in a circular economy. Organizations interested in delivering waste-efficient building projects can also use the identified competencies to recruit new BIM specialists and gauge the competency of existing staff in delivering waste-efficient projects.

Declaration of competing interest

There is no conflict of interest among the authors of this article.

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