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Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment

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ABSTRACT

The need to use Building Information Modelling (BIM) for Construction and Demolition Waste (CDW) minimisation is well documented but most of the existing CDW management tools still lack BIM functionality. This study therefore assesses the expectations of stakeholders on how BIM could be employed for CDW management. After a review of extant literature to assess the limitations of existing CDW management tools, qualitative Focus Group Interviews (FGIs) were conducted with professionals who are familiar with the use of BIM to understand their expectations on the use of BIM for CDW management. The 22 factors identified from the qualitative data analyses were then developed into a questionnaire survey. The exploratory factor analysis of the responses reveals five major groups of BIM expectations for CDW management, which are: *(i) BIM-based collaboration for waste management, (ii) waste-driven design process and solutions, (iii) waste analysis throughout building lifecycle, (iv) innovative technologies for waste intelligence and analytics, and (v) improved documentation for waste management.* Considering these groups of factors is key to meeting the needs of the stakeholders regarding the use of BIM for CDW management. These groups of factors are important considerations for the implementation and acceptance of BIM-based tools and practices for CDW management within the construction industry.

1. Introduction

Over the decades, building construction activities have generated the largest volume of waste across the globe (Osmani, 2013). This waste could be attributed to the constant uptake of construction, demolition and renovation activities during which villages are built into towns, towns into cities and cities into mega cities (Jaillon and Poon, 2014). In fact, this uptake of building activities results in about 30% of the total annual waste generation worldwide (Jun et al., 2011; DEFRA, 2015; EC, 2015). This thus puts immense pressure on the depleting landfill sites and affects the environment adversely. To ensure the conservation of natural resources and to reduce the cost and impacts of waste disposal, effective waste management practices must be put in place. This will ensure the flow of construction material in a closed loop to minimise waste generation, preserve natural resources and reduce demand for landfills. To achieve this, effective management strategies such as waste reduction, component reuse and material recycling are needed to divert Construction and Demolition Waste (CDW) from landfills (Oyedele et al., 2014).

Literature reveals that the largest percentage of CDW is caused by activities at pre-construction stages and that design decisions have high impact on CDW generation (Ajayi et al., 2016a,b; Faniran and Caban, 1998). Accordingly, effective decision-making mechanisms are needed during the design stages to minimise the impact of design changes. As a result, principles for designing out waste such as design for material optimisation, design for recovery and reuse, design for waste efficient procurement, design for off-site construction, as well as design for deconstruction and flexibility were developed (WRAP, 2009). Despite these opportunities to minimise CDW at the design stages, existing waste management tools (such as NETWaste, DoWT-B, SMARTWaste) are not, in reality,

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helpful to designers (Osmani et al., 2008). This is because they are completely detached from the design process and can only be used after the bill of quantities has been prepared. This makes it too late for architects and design engineers to make major design changes to minimise waste. Although several studies (Ajayi et al., 2015a; Liu et al., 2011; Porwal and Hewage, 2011) have identified that building information modelling (BIM) has potentials for designing out waste, none of the studies has provided clear instructions on how BIM could be used for this purpose. Besides, the lack of knowledge on stakeholders' expectations on the use BIM for CDW management raises serious concerns on how BIM could be implemented for CDW management.

In view of the foregoing and the knowledge gap identified, this study seeks to determine how the potentials of BIM could be harnessed to support CDW management and to understand the expectations of industry practitioners on BIM for CDW management. Accordingly, the specific objectives of the study include:

1) To identify the limitations of existing CDW management tools; and
2) To understand the expectation of stakeholders on how the use of BIM could enhance existing CDW management tools.

In order to identify inefficacies and limitations of CDW management tools, first, this study starts with an in-depth performance assessment of existing CDW tools. Afterwards, a qualitative study was conducted using multiple focus group interviews to understand how BIM could address the limitations of existing tools. This is to have an in-depth understanding of the phenomenon as experienced by stakeholders. Results from the analyses offer insight into the capabilities of BIM, especially those to be considered in improving the effectiveness of existing CDW management tools. The analyses reveal 22 factors that relate to the stakeholders' expectations on the use of BIM for CDW management tools, which were organised into a questionnaire to seek the opinion of a larger population concerning the use of BIM for CDW management.

The remaining sections of the paper are organised as follows: Section 2 contains a review of extant review of literature on the limitations of existing CDW management tools. Then, methodological approach adopted in this study is justified and discussed; this includes sampling technique, data collection, and data analysis methods. Findings of the study are presented before an analytical discussion of the roles of BIM in CDW management. The final part of the paper summarises implications in the event of practice and areas that could lead to further research.

2. Limitations of existing construction waste management tools

Knowing the limitations of existing CDW management tools is key to understanding how the capabilities of BIM could be used to improve them. To ensure broad perspective, studies were collected from a wide range of peer-reviewed journals using the Scopus search engine. Falagas et al. (2008) suggests that Scopus has higher accuracy and journal coverage compared to other databases such as Web of Science and Google Scholar. Besides, the Scopus database has been employed in literature search in construction related studies (Jiao et al., 2013; Osei-Kyei and Chan, 2015; Yuan and Shen, 2011). Afterwards, the papers were analysed to identify CDW management tools and their limitations. The review reveals that the tools can be categorised under five broad groups, which are: (i) waste management plan templates and guides; (ii) waste data collection and audit tools; (iii) waste estimation tools; (iv) environmental assessment tools and (v) waste Geographic Information System (GIS) tools. After an exhaustive review, five main limitations that impede the effectiveness and usability of existing construction waste management tools were identified. These limitations can be summarised thus:

(i) existing tools are completely detached from the design process,
(ii) existing CDW management tools lack interoperability capabilities,
(iii) construction and demolition waste data are not sufficient,
(iv) waste management responsibilities are not clear, and
(v) lifecycle assessment of waste performance is not available.

A summary of existing tools with respect to the year of latest version, locality, BIM compliance, and the five limitations is presented in Table 1. Further discussions on these five limitations are presented in the following sub-sections.

2.1. Existing CDW management tools are completely detached from the design process

The design process is usually an iterative process that contains three stages to meet the client's needs. The design process happens at RIBA (Royal Institute of British Architects) work stage 2 (concept design), stage 3 (developed design), and stage 4 (technical design) (RIBA, 2013). These design process stages help to determine design workflow, tools and software requirements, and to produce building design documents (such as building drawings, materials specification, CAD models, schedule of work, bill of quantity, etc.). Meanwhile, studies on sources of CDW (Faniran and Caban, 1998; Osmani, 2012; Oyedele et al., 2013; C. S. Poon et al., 2004a,b) show that the largest percentage of CDW occurs during the preconstruction (planning and design) stages. This is primarily due to making inappropriate design decisions, which leads to design changes (Osmani et al., 2008; Poon, 2007). Apart from design changes, other sources of CDW due to design include unfamiliarity with material alternatives (Ekanayake and Ofori, 2000), lack of knowledge about standard size of materials and dimensional coordination (Treloar et al., 2003), errors in contract documents and drawings (Bossink and Brouwers, 1996), industry cultural related factors (Ajayi et al., 2016a,b), etc.

Despite the general knowledge that taking the right decisions during design could minimise CDW, none of the existing tools has been fully integrated into the design process. Although some CDW management tools are engaged during the design process, they are not integrated into the design tools used by architects and engineers. Recent advancements in information and communication technology (ICT) have culminated in the development of various tools to assist construction industry stakeholders in CDW management; however, the tools are still external to the design process and they can only be used after design is completed. For example, NWT and DoWT-B, which is believed to produce a more accurate waste estimation (WRAP, 2011b), could only be used after the bill of quantity has been produced. Thus, this makes it difficult for architects and design engineers to identify possible ways of waste management during design. Besides, advice on waste minimisation at this point is too late and will require significant effort and time to implement.

Despite the increasing adoption of BIM in building design, most of the existing waste management tools are not BIM compliant (Cheng and Ma, 2013). This is because these tools are external to the BIM software used by designers, thereby limiting their usability. Out of the existing tools, only DRWE (Cheng and Ma, 2013) and BIM-DAS (Akinade et al., 2015) are BIM compliant. This fact reveals a huge gap in knowledge since evidence in literature suggest that effective waste minimisation must start from the design stage

Table 1
Existing tools for construction waste management and characteristics.

No.	Category	Tools (Reference)	Year	Locality	Positive Characteristics				
					A	B	C	D	E
1.	waste management plans and guides	Cost effective waste management plan (Mills et al., 1999)	1999	USA	✗	✗	✗	✗	✗
		Site Waste Management Plan (SWMP) (WRAP, 2008)	2008	UK	✗	✗	✗	✗	✗
		Material logistic plan (WRAP, 2007)	2007	UK	✗	✗	✗	✗	✗
		Designing Out Waste Guide (WRAP, 2009)	2009	UK	✗	✗	✗	✗	✗
		Procurement guidance (WRAP, 2010)	2007	UK	✗	✗	✗	✗	✗
		Demolition protocol (ICE, 2008)	2008	UK	✗	✗	✗	✗	✗
2.	Waste data collection tools	CALIBRE (Chrysostomou, 2000)	2000	UK	✗	✗	✗	✗	✗
		Webfill (Chen et al., 2003)	2003	Hong Kong	✗	✗	✗	✗	✗
		SMARTAudit (BRE, 2008)	2008	UK	✗	✗	✗	✗	✗
		SMARTWaste (Mcgrath, 2001)	2001	UK	✗	✗	✗	✗	✗
3.	Waste estimation tools	Waste index (C. S. Poon et al., 2004a,b)	2004	Hong Kong	✗	✗	✗	✗	✗
		Building waste assessment score (Ekanayake and Ofori, 2004)	2004	Singapore	✗	✗	✗	✗	✗
		Stock-Flow model (Bergsdal et al., 2007)	2007	Norway	✗	✗	✗	✗	✗
		Spanish model (Solís-Guzmán et al., 2009)	2009	Spain	✗	✗	✗	✗	✗
		Component-Global Indices (Jalali, 2007)	2007	International	✗	✗	✗	✗	✗
		Environmental Performance Score (Shen et al., 2005)	2005	China	✗	✗	✗	✗	✗
		Material Flow Analysis model (Cochran and Townsend, 2010)	2010	USA	✗	✗	✗	✗	✗
		Multiple regression model (Parisi Kern et al., 2015)	2015	Brazil	✗	✗	✗	✗	✗
		Net Waste Tool (NWT) (WRAP, 2011a)	2011	UK	✗	✗	✗	✗	✗
		Design-out Waste Tool for Buildings (DoWT-B) (WRAP, 2011b)	2011	UK	✓	✗	✗	✗	✗
		Demolition and Renovation Waste Estimation (DRWE) (Cheng and Ma, 2013)	2013	Hong Kong	✓	✓	✗	✗	✗
		DeconRCM (Banias et al., 2011)	2011	Greece	✗	✗	✗	✗	✗
		Web-based Construction Waste Estimation System (WCWES) (Li and Zhang, 2013)	2013	Hong Kong	✗	✗	✗	✗	✗
4.	Environmental assessment tools	Building end of life analysis tool (Dorsthorst and Kowalczyk, 2002)	2002	International	✗	✗	✗	✗	✗
		Sakura (Tingley, 2012)	2012	UK	✗	✗	✗	✗	✗
		Building deconstruction assessment tool (Guy, 2001)	2001	UK	✗	✗	✗	✗	✗
		BREEAM (BREEAM, 2015)	2014	UK	✗	✓	✗	✗	✗
		Athena environmental impact estimator (Athena, 2015)	2003	International	✗	✓	✗	✗	✗
		LEEDS (USGB, 2005)	2013	USA	✗	✓	✗	✗	✗
		BIM-based Deconstructability Assessment Score (BIM-DAS) (Akinade et al., 2015)	2015	International	✓	✓	✗	✗	✗
5.	GIS tools	BREMap (BRE, 2009)	2009	UK	✗	✗	✗	✗	✗
		Global Position System (GPS) and GIS technology (Li et al., 2005)	2005	International	✗	✗	✗	✗	✗
		GIS-BIM based supply chain management system (Irizarry et al., 2013)	2013	International	✗	✗	✗	✗	✗

A – Engaged design process, B – Software interoperability, C – Sufficient CDW data, D – Clear CDW management responsibility, E – Whole-life waste analysis.
✓ - functionality available, ✗ - functionality not available.

(Faniran and Caban, 1998; Wang et al., 2014) and this can only be achieved if waste management functionalities are incorporated into design tools.

2.2. Existing CDW management tools lack interoperability capabilities

Due to the emerging importance of BIM in the architecture, engineering and construction (AEC) industry, most companies have adopted BIM to improve multidisciplinary collaboration. Grilo and Jardim-Goncalves (2010) highlights that BIM ensures that all project teams can communicate easily, contribute to decision making and access information about the project. According to Gallaher (2004), lack of software interoperability in the USA, alone, resulted into a yearly loss of about $15.8 billion. Participating teams therefore expend immense effort to ensure software interoperability because teams have different software needs and varied expertise on software usage (Cyon, 2009; Hu et al., 2016). This consideration makes the adoption of BIM imperative within the construction industry to satisfy the requirements for software interoperability and effective collaborative practices (Ajayi et al., 2015b). This is to allow collaborating teams to exchange building models among BIM software without loss of information. Despite the current effort to achieve full software interoperability in the AEC industry, most of the existing CDW management tools lack interoperability capabilities with other software. Moreover, the process of how CDW management can be implemented in BIM collaborative environment has not been well documented. This gap has impeded the exploitation of the capabilities of BIM software for the analysis of CDW at the design stage.

The support for model exchange among heterogeneous BIM software is engendered by the development of BIM standards such as the industry foundation classes (IFC) (Laakso and Kiviniemi, 2012) and gbXML (Dong et al., 2007), etc. The BIM standards do not only provide means of cross-platform representation of building materials, but also the representation of building forms and functionalities. While IFC is generally acceptable as the industry standard (Eastman et al., 2011), its current implementation is not efficient to tackle the always changing demand of the AEC industry (Tibaut et al., 2014). According to Akinade et al. (2016), this limitation therefore constitutes a great problem that must be addressed by BIM and CDW practitioners considering the recent rate of BIM adoption and the environmental and economic benefits accruable from effective CDW management. Overcoming this challenge of software interoperability among CDW management tools and BIM software will engender the exploitation of BIM functionalities within CDW analysis tools and vice versa.

2.3. Construction and demolition waste data are not sufficient

Current efforts in CDW management have been focused on understanding how the waste output expected from building projects could be estimated at the design stage. Accordingly, existing CDW estimation tools calculate the waste potentials of buildings using historical regional or national waste generation rates and Gross Floor Areas (GFA) (Jalali, 2007; Li and Zhang, 2013; Poon et al., 2004a,b). However, Mills et al. (1999) highlighted that a major limitation of these models is insufficient waste data. In like manner, most waste estimation tools are developed using location specific information thereby making them not universally applicable. Consequently, the reliability of using these tools for CDW estimation in other locations could not be guaranteed (Mokhtar et al., 2011). For example, SMARTWaste (Mcgrath, 2001) estimates CDW from statistical waste data collected from previous building projects in the UK. This restriction limits the use of the tool in other countries. Even so, the accuracy of the waste data could not be guaranteed because data entry involves a high level of human intervention, which is prone to errors.

A major challenge to developing a robust CDW database is that most of the construction waste arising from building projects is not segregated (WRAP, 2011a). On further work, Mcgrath (2001) noted that unsegregated waste is mostly collected and transported as general waste. This therefore does not allow waste data to be properly labelled. In addition, majority of existing CDW estimation tools are based on aggregating waste indices and volumetric data despite the multi-dimensional nature of waste generation factors. This raises serious concerns because the tools were developed without adequate consideration for detailed material information and building methodology, among others. Notably, the peculiarities of building activities influencing CDW generation are quite disperse and treating them the same way could be misleading. For example, similar building designs in the same region but different locations cannot be treated in the same way despite their similar GFA and material specification. Therefore, the expectation of a robust waste estimation tool taps into the perceived degree of accuracy from relationship among specific factors, which goes beyond waste generation rate, construction activities, building materials, and historical waste data. Certain factors, such as soil type, construction methodology, design quality, and the competence of site workers are associated with waste output potentials of building models.

2.4. Waste management responsibilities are not clear

According to Ajayi et al. (2015a), waste generation in building projects is largely dependent on the attitude of stakeholders in taking up waste management responsibilities. Out of these stakeholders, clients make up the core of the building project process (Latham, 1994) and have the greatest influence on waste management issues. Understandably, clients set environmental standards that other stakeholders must meet. Similarly, Teo and Loosemore (2001) highlighted that implementing effective waste management strategies requires cooperation among all participating team, especially in accepting responsibilities towards CDW management. Examples of such waste management responsibilities include involvement in analysis of potential waste of project during design, organising and attending waste management meetings, training on waste management tools, setting waste management goals and preparing list of recoverable waste material to be reused or recycled. From these responsibilities, Osmani et al. (2008) show that only 2% of building project teams hold waste management meetings and that only 32% of them implemented management goals. This is primarily because most people believe that CDW is inevitable and can only be managed or ignored.

In addition, Osmani et al. (2008) highlights that poorly defined individual responsibilities have contributed to the laxness of individual's commitment to waste management. This gap reveals the need for a clear definition of stakeholders' responsibilities at an early stage of building projects. More importantly, this need is to create a synergy of roles on waste management strategies, goals, and choice of tools. To achieve this, contracts and contractual agreements are employed to assign decisive waste management responsibilities. As such, contractual clauses must be used to communicate waste management responsibilities and to penalise poor CDW performance as suggested by Dainty and Brooke (2004) and Greenwood (2003). Understandably, Poon et al. (2004a,b) suggest that sub-contractors could be assigned additional waste management duties. This is because sub-contractors could be willing to take more responsibilities at the same price due to high competition.

2.5. Lifecycle assessment (LCA) of CDW performance is not available

Lifecycle Assessment (LCA) is used to evaluate the impact of a process or product from its origin to the end of use on the environment (Ortiz et al., 2009). Existing studies on waste management and minimisation show that waste is produced throughout the building lifecycle (Jaillon and Poon, 2014; Kozlovská and Spišáková, 2013; Osmani, 2013; Yeheyis et al., 2013). This means that waste arises from design stages to the end of life of buildings. This makes LCA an important tool in CDW management planning and policy-making (Ekvall et al., 2007; Klöpffer, 2006). Accordingly, LCA offers environmental methodology for comparing waste management options. Despite the belief that LCA methodologies could be used for CDW management and minimisation (Llatas, 2011), none of the existing CDW management tools has functionality for LCA. This is because existing tools are useful at specific work stages (Liu et al., 2011) but not throughout the entire building life cycle. For example, tools such as SMARTWaste, SMARTStart, and Webfill are useful at only the construction stage (RIBA stage K). This however reveals a huge limitation because evidence shows that efficient waste management approach requires a "cradle-to-grave" appraisal of building projects (Guy et al., 2006; Morrissey and Browne, 2004).

Owing to the discussion of the five major limitations of existing CDW management tools, the aim of the study is to identify how BIM capabilities could be employed to address these limitations. This is towards an effort to improve the performance of existing CDW management tools and to understand the expectations of stakeholders in terms of using BIM for CDW management. The next section details the methodology employed in achieving the specific objectives of this study.

3. Research methodology

In exploring the expectations of industry stakeholders on the use of BIM for CDW management, this study adopts an exploratory sequential mixed methods research strategy. An exploratory sequential mixed methods research strategy starts with qualitative data collection and analysis (Onwuegbuzie et al., 2010) using focus group interviews (FGIs) and Atlas.ti respectively. This is immediately followed by quantitative data collection and analysis that employs the results of the first qualitative phase (Creswell, 2014). Quantitative data collection was done through a questionnaire survey and the data analyses were carries out using statistical package for social sciences (SPSS). Several benefits accrue from the integration of qualitative and quantitative data in a mixed methods research design. According to Fetters et al. (2013), chief among the benefits is the use of quantitative data analyses to explain and generalise findings from qualitative analysis. Accordingly, the focus of this mixed methods research design is to use the results of quantitative analysis to support the interpretations of the findings of the qualitative phase. The methodological flowchart for the study is presented in Fig. 1. The process starts with qualitative data collection and analyses and it proceeds to questionnaire survey development and administration. The responses of the questionnaire survey were subjected to rigorous statistical analyses using

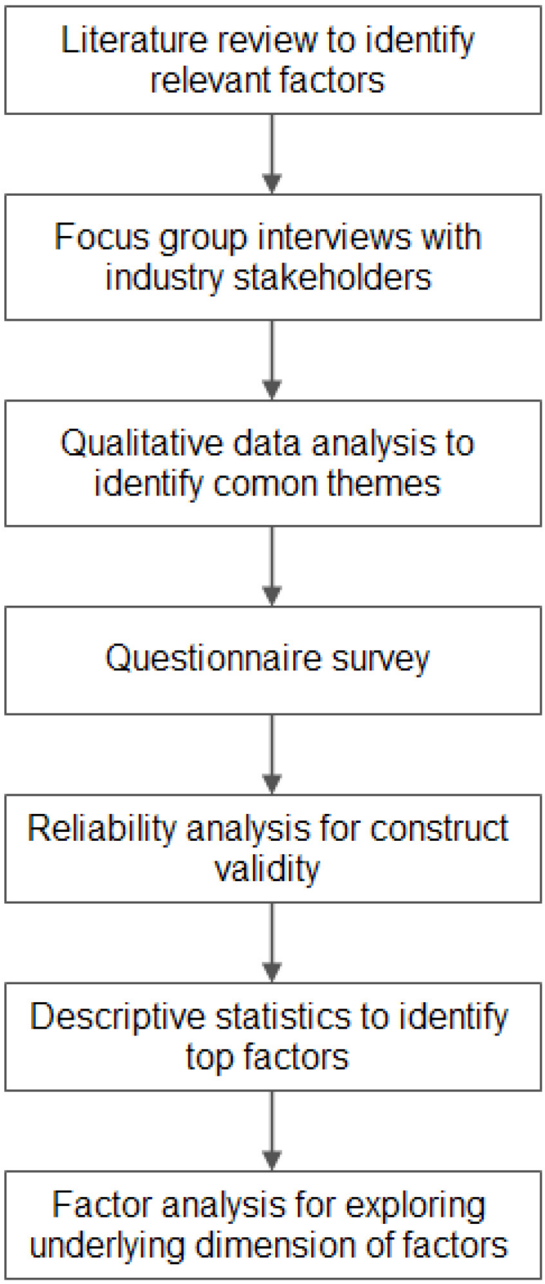

Fig. 1. Methodological flowchart for the study.

reliability analysis, mean ranking and exploratory factor analysis.

3.1. Qualitative data collection and analysis

After identifying the limitations of existing CDW management tools, a qualitative interpretative study was carried out to understand how effective design out waste process could be achieved by employing current capabilities of BIM and to understand the expectations of stakeholders. According to Creswell (2014), a qualitative interpretative methodology seeks to exhume common meaning from the experiences of several individuals. According to Moustakas (1994), two data collection methods that dominate qualitative research are in-depth interviews and Focus Group Interviews (FGIs). In-depth interview is conducted to elicit participants' perspective of a phenomenon, while focus group interview particularly involves discussion among selected group of participants regarding a common experience (Hancock et al., 1998). This study chose FGI over individual interviews with participants because FGIs allow participants to discuss their personal opinions based on their experiences and they allow participants to build on the responses of others. This provides deeper insights into a wide range of perspectives within a short time.

Accordingly, multiple FGIs were conducted with participants selected from the UK construction companies who have partially or fully implemented BIM on their projects. Convenience sampling was adopted in a way that individuals who are directly involved in building design, BIM, and construction waste management were chosen. Although the stakeholders are not specialists in BIM tool development, understanding their views and expectations could help to uncover and analyse the industry requirement of BIM in CDW management across different disciplines. In addition, end users are key in the engineering of any useful innovation development (Oyedele, 2013) and their views and expectations need to be taken into consideration. Accordingly, 23 professionals were selected based on suggestion of Polkinghorne (1989) who recommended that FGI participants should not exceed 25. The distribution and the range of years of experience of the participants of the five FGIs (FGI1 to FGI5) are shown in Table 2.

Participants of the FGIs were encouraged to discuss their expectations on the use of BIM for waste management. This was done with the aim of understanding the possibilities of addressing limitations of existing waste management tools with the current capabilities of BIM. Individual FGI lasts from 45 min to 60 min and the FGIs were carried out at different times. Discussion and interactions among participants were recorded on a digital recorder and later compared with notes taken. This is to ensure that all important and valuable information to the study were captured. Afterwards, the voice recordings were transcribed and segmented for thematic analysis using Atlas.ti. These tasks were conducted to develop clusters of meanings by themes identification (coding).

In a qualitative interpretative research, data analysis follows structured methods, which starts with the description of researchers' own experiences followed by the description of textual and structural discussions of participants' experiences (Creswell, 2013). The voice transcript was transcribed and significant statements (quotations) were identified. The significant statements were then grouped together into themes to identify units of meaning on Atlas.ti. The factors from the qualitative data analyses

Table 2
Overview of the focus group discussions and the participants.

FG	*Categories of participants*	*No of participants*	*Years of experience*
FGI1	Architects and design managers • 3 design architects • 1 site architects • 2 design managers	5	12–20
FGI2	M&E Engineers • 2 design engineers • 2 site engineers	4	9–22
FGI3	Construction project managers	5	12–22
FGI4	Civil and structural engineers • 2 design engineer • 3 site based engineers	5	8–18
FGI5	BIM specialist	4	8–12
Total		23	

and from the literature review were then put together into a questionnaire survey and analysed accordingly.

3.2. Quantitative data collection and analyses

After the review of extant of literature and FGIs, 22 factors that relate to the industry expectations on the use of BIM for CDW management were identified. These factors were then organised into a questionnaire survey and a pilot study was carried out before sending the questionnaire out to the respondents. The participants of the pilot study include five architects and two construction project managers. The final version of the questionnaire is then produced by considering the comments received from the pilot study. The final questionnaire is made up of three sections, which are: (i) survey cover letter to explain the purpose of the survey, (ii) particulars of respondent to capture information about respondents, and (iii) body of questionnaire, where the respondents were required to indicate the importance of the factors on a five-point Likert scale, where 1 represents 'not important' and 5 represents 'most important'. This section also includes a textbox for additional comments from the respondents.

By employing the directory of a UK construction company and purposive sampling, 130 respondents were selected for the survey. The response rate of the survey was 47.7%, which indicates that only Sixty-two (62) respondents could adequately respond to the survey. This is because of the purposive sampling approach that enforces a selection criteria on the respondents' selection. The criteria used are hands on experience with BIM tools and an understanding of the UK sustainability agenda. Three of the submitted questionnaires were incomplete and discarded, thus leaving only 59 usable responses for analyses (45.4%). The demographic distribution of respondents is as shown in Table 3. The respondents include 14 architects, seven M&E engineers, 19 project managers, seven civil/structural engineers, five BIM/lean specialists, and seven design managers. The responses were then analysed using SPSS. The responses of the questionnaire survey were then subjected to a rigorous statistical process to identify the expectations of industry stakeholders on BIM adoption for CDW management. The statistical analyses include reliability analysis, descriptive statistics, and exploratory factor analysis.

3.2.1. Reliability analysis

Reliability analysis was carried out to check if the 22 factors in the survey and their associated Likert scale consistently reflect the construct the study intends to measure (Field, 2005). Accordingly, Cronbach's alpha coefficient of reliability (α) was calculated for the factors using Equation (1).

Table 3
Sample data of questionnaire survey.

Data of questionnaire survey	Sample size
Total questionnaire sent out	130
Total of submitted responses	62 (47.7%)
Discarded responses	3 (2.3%)
Total number of usable responses	59 (45.4%)
Years of experience in construction industry	
0–5 years	6
6–10 years	10
11–15 years	20
16–20 years	13
21–25 years	6
Above 25 years	4

$$\alpha = \frac{N^2\overline{COV}}{\sum_{i=1}^{N} S_i^2 + \sum_{i=1}^{N} COV_i} \tag{1}$$

Where N is the total number of the factors; $\overline{COV}$ is the average covariance between factors; S_i^2 and COV_i are the variance and covariance of the factors '*i*' respectively. The Cronbach's α has a value from 0 to 1 and the higher the value ofα, the greater the internal consistency of the data (Field, 2005). According to Field (2005), it is generally believed that a value of $\alpha = 0.7$ is acceptable and $\alpha > 0.8$ depicts good internal consistency. The calculated α for this study is 0.915, which demonstrates a very good internal consistency of the data. The "*Cronbach's alpha if item deleted*" of each factor was then examined to confirm that all the factors are contributing to the internal consistency of the data. It is good practice to delete factors whose "*Cronbach' alpha if item deleted*" is higher than the overall coefficient to improve the overall reliability of the data. Accordingly, one of the factors was deleted. The remaining 21 factors were then ranked using descriptive statistical mean as a ratio of importance. The results of the reliability analysis and ranking of the factors is shown in Table 4.

The mean ranking reveals that "*computer aided simulation scenario and visualisation of waste performance*" is the most significant stakeholders' expectation on the use of BIM for CDW management. This is because the construction industry is long overdue for BIM-based prediction and simulation platforms for waste performance of building models (Bilal et al., 2016b). It is not a surprise that "*embedding waste-related information into building model*" was ranked second. This affirms the results of other studies that identified that the need for embedding CDW related information into buildings models (Bilal et al., 2016a). A major requirement for this is knowing what information is needed and how to integrate it within existing standards. Achieving this will provide an opportunity to enhance the performances of existing CDW management tools and to develop better tools for CDW performance analysis. The other three top factors include "*decision-making on waste reduction during design*", "*support for whole-life waste analysis*", and "*interoperability among waste management tools and BIM software*". Achieving accurate design-based decisions on waste reduction requires that waste analytics functionalities are embedded into BIM software. These functionalities include waste prediction, waste minimisation and interactive visualisation. Support for waste analysis throughout the building lifecycle is important to understand the waste performance from design to the end of life of buildings. Achieving this in CDW management tools will make them relevant to all work stages. Interoperability among waste management tools and BIM software will ensure that waste management tools are able to leverage on the parametric modelling, visualisation and simulation capabilities of existing BIM software.

3.2.2. Exploratory factor analysis

The exploratory factor analysis identifies the underlying dimension of the factors. This is to replace the entire set of factors with a smaller number of uncorrelated principal factors. The factor analysis employed principal components analysis (PCA) with orthogonal rotation (varimax) of the 21 factors. The PCA was used for factor extraction and varimax rotation was used as factor rotation. The Kaiser-Meyer-Olkin (KMO) value and the Bartlett tests of sphericity were 0.518 (above 0.5) and 6.8×10^{-49} (less than 0.5) respectively. These values show the suitability of the data for factor analysis. The PCA results reorganises the list of factors into five groups, which account for of the total variance of 84.231% as shown in Table 5. Accordingly, the groups were then interpreted and labelled based on the factors assigned to the groups. The groups

Table 4
Reliability analysis and ranking of critical factors for designing out waste.

No	*Critical factors*	*Mean*	*Cronbach's alpha if item deleted*	*Rank*
V14	Computer aided simulation scenario and visualisation of waste performance	4.82	0.909	1
V2	Embedding waste-related information into building model	4.64	0.915	2
V1	Decision-making on waste reduction during design	4.58	0.906	3
V12	Support for whole-life waste analysis	4.50	0.914	4
V7	Interoperability among waste management tools and BIM software	4.48	0.907	5
V9	Early supply-chain integration for waste management decisions	4.36	0.907	6
V18	Foster task harmonisation among stakeholders to reduce duplication of effort	4.24	0.902	7
V6	Automatic generation of waste related documents	4.17	0.907	8
V3	Support for waste management innovations such as RFID, IoT, big data etc.	4.13	0.913	9
V4	Improved cost-benefit analysis of construction waste management	4.02	0.914	10
V13	Preservation of building information in COBie	3.92	0.910	11
V5	Improved materials classification methods	3.87	0.910	12
V19	Improved clash detection in building models to reduce waste	3.80	0.913	13
V11	Improved waste information sharing among stakeholders using BIM	3.73	0.906	14
V8	Automatics capture of design parameters for waste analysis	3.56	0.905	15
V21	Usage of BIM as a co-ordination tool for designing out waste	3.51	0.911	16
V22	Improved contractual document management	3.44	0.904	17
V15	Use of 3D printing for prefabrication	3.36	0.911	18
V10	Improved waste minimisation commitment among stakeholders	3.25	0.903	19
V16	Transparency of responsibilities during design process	3.24	0.903	20
V17	Allows the development of BIM federated model for use by all teams	3.22	0.911	21
V20	*Capability to capture clients' requirements	3.18	0.916	23

Overall Cronbach's alpha is 0.915; * - factors deleted based on higher value of Cronbach's alpha if item deleted. RFID (Radio-frequency identification) uses tags and electromagnetic fields to identify and track objects; IoT (internet of things) is a network of physical objects that enables them to exchange data; big data is a collection of voluminous, unstructured and complex dataset that traditional software cannot process.

Table 5
Component labelling and corresponding groups from exploratory factor analysis.

No	*ID*	*Groups and factors*	*Eigen value*	*% of variance*	*Factor loading*
		A. BIM-based collaboration for waste management	14.07	32.246	
1	V11	Improved waste information sharing among stakeholders using BIM			0.918
2	V18	Foster task harmonisation among stakeholders to reduce duplication of effort			0.867
3	V10	Improved waste minimisation commitment among stakeholders			0.866
4	V16	Transparency of responsibilities during design process			0.776
5	V9	Early supply-chain integration for waste management decisions			0.684
6	V17	Allows the development of BIM federated model for use by all teams			0.681
7	V21	Usage of BIM as a co-ordination tool for designing out waste			0.920
		B. Waste-driven design process and solutions	6.53	24.385	
8	V2	Embedding waste-related information into building model			0.957
9	V19	Improved clash detection in building models to reduce waste			0.928
10	V5	Improved materials classification methods			0.692
11	V6	Automatic capture of design parameters for waste analysis			0.619
12	V1	Decision-making on waste reduction during design			0.912
13	V4	Improved cost-benefit analysis of construction waste management			0.589
14	V14	Computer aided simulation scenario and visualisation of waste performance			0.714
		C. Waste analysis throughout building lifecycle	4.00	10.971	
15	V12	Support for whole-life waste analysis			0.899
16	V13	Preservation of deconstruction information in COBie			0.828
		D. Innovative technologies for waste intelligence and analytics	2.97	9.989	
17	V3	Support for waste management innovations such as RFID, IoT, big data etc.			0.943
18	V15	Use of 3D printing for prefabrication			0.942
19	V7	Interoperability among waste management tools and BIM software			0.604
		E. Improved documentation for waste management	2.38	6.640	
20	V6	Automatic generation of waste related documents			0.866
21	V22	Improved contractual document management			0.680
				84.231	

include:

(a) Group 1 denoted by improved collaboration for waste management
(b) Group 2 denoted by waste-driven design process and solutions
(c) Group 3 denoted by waste analysis throughout building lifecycle

(d) Group 4 denoted by Innovative technologies for waste intelligence and analytics, and
(e) Group 5 denoted by improved documentation for waste management

4. Expectations of industry stakeholders for BIM-based CDW management

Each of the expectation factors and how the expectations could be achieved are further discussed below.

4.1. BIM-based collaboration for waste management

The adoption of BIM for improved collaboration for waste management has the highest value among the groups with a total variance of 32.246% and it is made up of seven factors. This being the highest ranked factor is not a surprise because adequate collaboration and effective communicate is critical to the success of projects (Oyedele, 2013). In this regard, BIM plays a major role in ensuring that all stakeholders are actively involved in decision-making right from the conception of the building project through its entire lifecycle (Eadie et al., 2013a). The major benefit of adopting BIM for waste management is that it enables the creation of a federated model that could be assessed and updated by all the project team. This idea helps to improve the allocation and monitoring of responsibilities and encourages *shared risk and reward'* philosophy. The "*shared risk and reward*" engenders process efficiency, harmony among stakeholders, reduced litigation and prevents the culture of blame-game as well as the transfer of responsibilities (Eadie et al., 2013a). The use of BIM will also engender design coordination, task harmonisation, clash detection, and process monitoring of CDW management activities.

Despite the evidence from previous studies that BIM has the potentials for waste minimisation, no clear instructions have been provided on achieving this. The discussions from the FGIs corroborated this because the participants are aware of the potentials of BIM; however, none of them has adopted BIM for CDW management. While deliberating on the opportunities obtainable from the adoption of BIM for CDW management, it was argued that incorporating waste management functionalities into BIM would encourage effective participation of all projects teams in making waste management related decisions. In addition, the participants of the FGIs posit that BIM based design tools must incorporate features that will ensure that participating teams can collaborate effectively on waste management issues. These tools could be in form of plugins to existing BIM software to extend their functionalities.

4.2. Waste-driven design process and solutions

This group accounts for 24.385% of the total variance and contains seven factors. After an extensive consideration of the factors brought together under this group, the name "*waste-driven design process and solutions*" was chosen because all the sub-factors contribute towards design-based analysis of building waste performance. Performance analyses of buildings provides a platform for functional evaluation of buildings before the commencement of construction (Eastman et al., 2011). This functionality has aided the wide acceptability of BIM in the AEC industry to improve the performance of the form and functions of buildings right from the design stage (Manning and Messner, 2008). This allows comparison of alternative design options to select the most cost-effective and sustainable solution. At the same time, de Magalhães et al. (2017) highlights that performance evaluation of design models helps to identify possible design and operational errors issues at a stage where design changes are cheaper; thus, reducing waste.

In keeping with the foregoing facts, the participants agreed that the increasing popularity of BIM in the AEC industry has strengthened the development of various tools for design analyses, such as cost performance, energy consumption, lighting analysis, acoustic analyses, etc. Majority of these tools are provided as plugins on existing BIM software to carry out specific design analysis. Despite the benefits of building performance analyses and the environmental/economic impacts of construction waste, none of the existing BIM software has capabilities for waste performance analysis. This gap calls for a rethink of BIM functionalities towards capacity for waste simulation right from early design stages.

While IFC is generally regarded as the industry standard for interoperability (Eastman et al., 2011), its current implementation is not equipped with adequate mechanism to streamline challenges of the AEC industry such as construction waste analysis (Tibaut et al., 2014). This is because the current IFC implementation does not incorporate enough information to facilitate waste information analysis. This gap calls for a closer look into how IFC could be extended to support data exchange between CDW management tools and BIM software. Accordingly, the requirement and schema for information exchange among CDW management processes needs to be identified and captured within existing BIM standards. Achieving this would enable CDW management tools to exploit BIM standards to read and interpret parameters of building models for waste analysis.

In agreement with earlier studies (Eastman et al., 2011), the participants of the FGIs agreed that another benefit of BIM is parametric modelling, which enables automatic capture of design parameters for performance analysis. Accordingly, it was highlighted that employing BIM during design would eliminate human error during data entry. For example, CDW management tools such as NWT, DoWT-B and waste estimation models require practitioners to manually transfer design parameters from the bill of quantity. This approach therefore makes these tools susceptible to errors in waste estimation and it requires more effort and time.

4.3. Waste analysis throughout building lifecycle

This group produces a total variance of 10.971% and contains two factors. While discussing the role of BIM in lifecycle performance of buildings, the participants of the FGI agreed that the use of BIM encompasses all project work stages from the planning stage to the end of life of buildings. So, information on building requirements, planning, design, construction and operations can be amassed and used for making management related decisions on facilities. Accordingly, BIM allows all teams to embed relevant project information into a federated model. For instance, project information such as project schedule, cost, facility management information, etc. could be incorporated into BIM using COBie format. Preserving information throughout the lifecycle of buildings is important for effective facility management and end-of-life decisions for buildings. The extra information thus enables powerful modelling, visualisation and simulation viewpoints, which help to identify design, construction, operation, and end-of-life related problems before they occur. This distinguishing feature makes BIM applicable to all work stages by accumulating building lifecycle information (Eadie et al., 2013b). Although many stakeholders in the AEC industry understand the benefits of adding more information into models, which could extend parametric BIM into 4D, 5D, 6D, etc., no BIM dimension has been developed for waste management.

In addition, improved lifecycle management of building offered by BIM encourages data transparency, concurrent viewing, and editing of a single federated model, and controlled coordination of information access (Grilo and Jardim-Goncalves, 2010). In this way, BIM helps to address interdisciplinary inefficiency (Arayici et al., 2012) within the fragmented AEC industry throughout the building life-cycle. This will certainly improve team effectiveness while reducing project cost and duplication of effort. The participants agreed that although more time is required to create a federated model, its benefits surpass the cost. The participants of the FGIs highlight that since waste is generated at all project work stages, adopting BIM for waste management will allow effective capturing of waste related data from design to the end of life of buildings.

4.4. Innovative technologies for waste intelligence and analytics

The group "*innovative technologies for waste intelligence and analytics*" accounts for 9.989% of the total variance and it contains three factors. The implementation of BIM relies on the appropriate use of technologies and their effective integration into the design process. Synthesising emerging technologies such as Internet of Things (IoT), GPS, big data analytics and RFID helps to provide real-time building performance monitoring and analyses (Bilal et al., 2016a). An integration of these technologies into BIM facilitates location-based services, tagging and identification of building materials, remote collection of building data, etc. In terms of CDW management, RFID could be used to tag construction materials with waste information and GPS could be employed to track CDW movement. For example, RFID tags could be embedded into building components to collect waste related data arising from projects. This will help to scale the hurdle of waste data deficiency by providing technology-enabled methods for waste data tracking and collection. Achieving this will enable the full automation of waste data collection and analyses of waste performance of buildings.

In addition, technological support such as 3D printing could empower BIM for computer-controlled prefabrication of building components. This approach would improve design flexibility as components could be designed and printed to specification without material waste. Accordingly, synthesising these emerging technologies into BIM computational platform will eventually favour prefabs and modular construction, which will in turn yield significant reduction in the generation of CDW.

Although one could argue that the adoption of BIM is on the rise (Arayici et al., 2011), a major challenge confronted by construction companies is the issue interoperability between BIM and these new technologies (Steel et al., 2012). Accordingly, standards such as IFC (ISO 16739:2013) for seamless exchange of information among software, IFD (ISO 12006–3:2007) to harmonise and structure construction terms, and IDMs (information delivery manuals) (ISO 29481–1:2010) to unite construction processes for collaborative practices are adopted to scale the hurdle of interoperability. In addition, the communication standards such as oBIX (open Building Information Exchange) and IFG (IFC for GIS) have enabled building systems to communicate with enterprise applications such as cloud based and location based services.

4.5. Improved documentation for waste management

This group contributes 6.640% of the total variance and the group is composed of two factors. Due to the increasing sophistication of buildings, the need for more information for construction, operation, maintenance, and end-of-life activities has become vital (Jordani, 2010). This information is important to track building construction process, performances of building elements, isolate operation inefficiencies, and to respond to specific client's requests. Evidence shows that design quality and documentation forms an important requirement for successful building construction and facility management (Andi and Minato, 2003; Gann et al., 2003). In addition, the quality of design documentation could influence the end of life activities of buildings such as demolition and deconstruction. Albeit, Goedert and Meadati (2008) illustrate that BIM has capabilities to: (i) capture building design and construction process documentation, (ii) provide full inventory of elements and (iii) sustain the relevant information throughout the building lifecycle. This is because the use of BIM and COBie has enabled stakeholders to embed relevant facility maintenance information into building models.

In line with the foregoing, building documentations such as project schedule, cost profile, site waste management, site information sheet, complain/incidence logbook, traffic management plan, deconstruction plan, etc. could be incorporated from BIM models. Accordingly, the capability to capture design parameters enables on-demand extraction of the documents from the building models. Achieving this will therefore improve design coordination, time management and engineering capabilities to avoid human errors that could lead to the wastage of resources (Sacks et al., 2010). For example, architects may generate design drawings with accuracy and high level of detailing for fabrication. Likewise, the same concept could be adopted for CDW management waste reporting and the development of waste management plans.

5. Conclusion

It is generally accepted in the literature that the best approach to CDW management is minimisation through design. This is because design based philosophy offers flexible and cost-effective approach to waste management before it occurs. Accordingly, architects and design engineers have responsibilities to ensure that waste is given high priority in addition to project time and cost during design. Designers are therefore encouraged to advise stakeholders on the economic and environmental benefits of waste management, initiate waste management for other work stages, and improve general design practices towards waste minimisation. Despite the willingness of architects and design engineers to carry out these duties, existing waste management tools cannot support them effectively. Besides, none of the existing CDW management tools is BIM compatible despite the benefits of BIM in improving building process performances. From the foregoing, this paper assesses limitations of existing construction waste management tools and identifies the expectations of industry stakeholders in using BIM capabilities in addressing the limitations of existing tools. The study employs mixed methods approach after a review of extant literature on existing waste management tools and their limitations.

After conducting a review of extant literature, five limitations impeding the effectiveness of existing CDW management tools were identified. After this, a set of FGIs was conducted with professional from the construction industry to identify their expectations in terms of adopting BIM for CDW management. The factors identified from the literature review and the FGIs were then organised into a questionnaire survey to test the opinion of a wider population of stakeholders. The results of the factor analyses of the responses reveal five group of factors, which include "*BIM-based collaboration for waste management*", "*waste-driven design process and solutions*", "*waste analysis throughout building lifecycle*", "*Innovative technologies for waste intelligence and analytics*", and "*improved documentation for waste management*".

In a summarised discussion, this study presents dual contributions: (i) the results of this study improve the understanding of BIM functionalities and how they could be employed to improve the effectiveness of existing CDW management tools, and (ii) the understanding of the industry expectation on the use of BIM for CDW management will improve the implementation of BIM-based software prototypes for CDW management. In addition, the study revealed that harnessing current technological capabilities into BIM would help to achieve unprecedented CDW analysis performance. These contributions have significant implications for CDW research and industrial practices. The results highlight the current potentials of BIM in driving effective design-out-waste process and providing a basis for the development of BIM-based CDW management tools. Accordingly, BIM software and CDW management tools developers would benefit from the results of this study by providing deeper understanding of what is required to encourage the industry wide adoption of BIM-based waste management.

Despite the contributions of this study, a major limitation is that the participants of the FGIs were drawn from the UK only. The results should therefore be interpreted and used within this context. Other studies can explore transferability of findings from this study to other countries. In this way, the result of this study could provide a basis for comparative study with other countries. In addition, the results of this study should be interpreted with caution because of the sample size used. The sample size of the survey was small because the requirement of the questionnaire limits those that can respond to the questionnaire. Future studies should therefore endeavour to use larger sample size to achieve a broader generalisability.

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