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Evaluation Criteria for Construction Waste Management Tools: Towards a Holistic BIM Framework

Abstract

4 This study identifies evaluation criteria with the goal of appraising the performances of existing 5 construction waste management tools and employing results in the development of a holistic 6 Building Information Modelling (BIM) framework for construction waste management. Based 7 on the literature, this paper identifies 32 construction waste management tools in five 8 categories, which include tools for waste data collection and auditing, waste prediction, waste 9 quantification, waste management planning, and location-enabled services. After reviewing 10 these tools and conducting four focus group interviews, findings reveal six categories of 11 evaluation criteria, which include waste prediction potentials, availability waste data, Building 12 Information Modelling compliance, design, commercial and procurement consideration, and 13 technological consideration. Next, the performance of the tools was assessed using the 14 evaluation criteria and the result reveals that existing tools are not robust enough to tackle construction waste management at the design stage. The paper therefore discusses the 15 16 development of a holistic BIM framework with six layers: application, service domain, BIM 17 business domain, presentation, data, and infrastructure. The BIM framework provides a holistic 18 approach and organises relevant knowledge required to tackle construction waste effectively at 19 the design stage using an architecture-based layered approach. This framework will be of 20 interest to software developers and BIM practitioners who seek to extend the functionalities of 21 existing BIM software for construction waste management.

22

Keywords: Construction Waste Management Tools; Building Information Modelling;
Evaluation Criteria; Waste Prediction; Thematic Analysis; Waste Data; Framework

25

26 Introduction

In 2012, 25% of about 100 million tonnes of Construction, Demolition, and Evacuation Waste (CDEW) generated in the UK was sent to landfills [1]. According to Osmani [2], this percentage of waste requires a payment close to £200 million as annual landfill tax. Apart from the high landfill cost, the disposal of waste has resulted in severe ecological damage [3,4], shortage of land [5], increased transportation and project cost [6], etc. The constant increase in landfill charges instituted by most countries to discourage waste disposal [7] has not checked the amount of CDEW sent to landfills yearly [8]. Still, the volume of waste sent to landfill sites is a major concern owing to the cost of waste disposal and its adverse environmental impacts. To avoid the undesirable impacts of waste disposal, there is need for an overall change in strategy towards the preservation of the finite natural resources, the reduction in demand for landfill, and the reduction in the total project cost. According to Ajayi *et al.* [9], a number of construction waste management strategies, from which waste reduction is most desired, have been developed to ensure a tighter loop of material and building components .

8 In spite of the consensus in the literature that CDEW could be reduced through design [2,10–14], 9 still waste minimisation is not given priority during design [12,15]. The opportunities in 10 designing out waste have motivated various stakeholders to develop initiatives such as 11 "designing out waste" by Waste and Resources Action Programme (WRAP) and SMARTWaste 12 by Building Research Establishment (BRE). The UK government has also commissioned waste 13 minimisation and sustainability initiatives which include "halving waste to landfill by 2012 14 relative to 2008" [16], "Zero waste to landfill by 2020" [17], and Site Waste Management Plan 15 (SWMP) Regulation. Likewise, the United States Environmental Protection Agency (USEPA) 16 has also set targets to characterise and understand CDEW material stream as well as promoting 17 research on best practices for CDEW reduction and recovery. This suggests an operational shift 18 from on-site waste management to design based waste management [14]. It is believed that 19 techniques in BIM could be adopted by the design team in these directions for waste minimisation 20 [13,18].

21 A recent survey of 1,350 UK construction professionals by National BIM Survey [19] reveals an 22 uptake in the adoption of BIM from 13% in 2010 to 39% in 2012, meaning that the UK now 23 ranks alongside USA, Finland, Singapore, New Zealand, Hong Kong etc. The increasing 24 adoption of BIM has revolutionised the construction industry [20] by improving system 25 interoperability [21], information sharing, visualisation of n-D models and decision making 26 processes. BIM also provides a platform for seamless collaboration among stakeholders [22] 27 from different disciplines. BIM knowledge therefore taps into various fields, which include 28 project management, construction, engineering, information technology, policy and regulation, 29 etc., and the expectations of BIM cut across these fields [23]. Considering the numerous benefits 30 of BIM, such diverse knowledge needs to be systematically structured in an efficient way to 31 enhance the understanding and graceful development of BIM. This thus reveals the need for a framework to organise the different modules and components of BIM into an integrated system,
 and to establish the relationships and interactions among the modules and components.

3 Based on the Industry Foundation Classes (IFC) Specification framework [24] (buildingSMART, 4 2013), a number of BIM frameworks [23,25–28] and Cloud-based BIM frameworks [29–32] 5 have been developed. These studies show that an integration of BIM could foster early decision making throughout a project lifecycle [33,34]. However, none of the existing BIM frameworks 6 7 has comprehensively captured the construction waste management domain. So considering the 8 year 2016 deadline for the adoption of full collaborative 3D BIM [35] and the benefits of CDEW 9 management, integrating waste minimisation into BIM constitutes a huge opportunity for the 10 construction industry. This will lead to a cultural change within the industry for the adoption of 11 BIM towards sustainable construction [9].

12 The increasing attention received by CDEW from the industry and academia and the recent 13 advancement in Information and Communication Technologies (ICT) and Computer Aided 14 Design (CAD) technologies has favoured the development of various tools to assist practitioners 15 in the implementation of waste management strategies and processes. In fact, computer support 16 is indispensable in construction related tasks in order to achieve the required flexibility, 17 reliability, and efficiency [36] [37]. It is on this basis that this study aims explore a synergy of 18 BIM applications and existing waste management tools to investigate critical evaluation criteria 19 for assessing their performances. After which the study explores an intersection of research 20 frontier in computer science, waste management and building construction studies by developing 21 a holistic framework composed of operational and technological requirements needed for the 22 implementation of a holistic BIM-based waste management tool. Therefore, the main research 23 questions for the study are:

- What are the key evaluation criteria that could be used to assess the performances of
 existing construction waste management tools?
- How could the key evaluation criteria be utilised in the development of a holistic BIM
 framework for construction waste management?

This study relies on a thorough review of extant literature and Focus Group Interviews (FGIs) to identify a list of evaluation criteria for existing CDEW management tools. The transcripts of the 1 FGIs were subjected to thematic analysis to reveal the underlying structure of the criteria. The 2 contributions of this study include: (i) providing a set of criteria to evaluate existing and future 3 waste management tools; (ii) to providing a robust application architecture for extending the 4 functionalities of existing BIM software by leveraging on their parametric modelling, APIs, 5 robust material database, and interoperability support for implementing of plugins for construction waste management. Software developers might seek to utilise the important 6 7 components and structure of the holistic BIM framework to improve the performances of existing 8 construction waste management tools.

9 Literature Review: Existing Construction Waste Management Tools

The increasing research interest in CDEW management has resulted into numerous scholarly publications, and various studies have been carried out to examine the trend of research journal publication in this field [3,38,39]. These studies reveal that current research trends in construction waste management can be characterized into six perspectives as shown in



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- Figure 1. These studies identified construction waste management tools as the key driver for successful implementation of waste management practices. Although, a number of independent studies influenced the current study, no study exists that critically assesses existing waste
- 18 management tools with respect to their functionalities and performances.

1 After a compilation of relevant papers from peer reviewed journals, a filtering process was 2 carried out to ensure the papers match the research scope. This was done by scanning the titles 3 and abstract, and imposing certain exclusion criteria to remove papers outside the scope of this 4 study. As such, publications on nuclear/radioactive waste, municipal solid waste and waste from 5 electronic and electrical equipment were excluded. The scope of the literature review is to include publications that have direct impacts on construction waste management. After the filtering 6 7 process, 22 tools were identified from the collected papers. Thereafter, a cross-examination of 8 the papers identified was done by manually scanning through the references cited. Afterward, 10 9 additional tools were identified, thus bringing the total number of tools to 32. After a careful assessment of the primary functions of these tools identified from the literature review, five broad 10 classifications of tools emerges, which include: (i) waste management plan templates and guides, 11 (ii) waste data collection and audit tools (iii) waste quantification models, (iv) waste prediction 12 13 tools (v) GIS tools. The five classifications along with their associated tools are as illustrated in Figure 2, and their corresponding descriptions are given in the following sections. 14



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Figure 1: Studies in Construction Waste Management



Figure 2: Current Waste Management Tools

3 Waste Management Plan Templates and Guides

1

2

4 A typical Waste Management Plan (WMP) captures information such as quantities and 5 specification of materials, procurement details, volume of waste generated, costs (transportation, 6 labour, and disposal), etc. to determine the economic and environmental feasibility of waste 7 management. As such, WMPs provide automated spreadsheet templates to facilitate the 8 computation of variables of interest such as waste output and costs. Examples of WMPs include 9 Cost Effective Waste Management Plan [40], Site Waste Management Plan (SWMP) [41], and 10 Material Logistic Plan [42]. A major critique to the development of WMPs is the reliability of the data and the accuracy of computation on which the economic and environmental comparisons 11 12 of alternative strategies are based [40].

On the other hand, a Waste Management Guide (WMG) provides a list of steps to assist waste
 practitioners to identify possible areas for waste minimisation. Examples of WMG include
 Designing out Waste Guide [43,44], Procurement Guidance [45], and Demolition Protocol [46].

In spite of the relevance of these guides, they failed to identify direct and indirect design waste origin, causes and sources, which could inform the implementation of the design-out-waste principles [14].The guides also lack appropriate design parameters required for the coordination of processes and communication among stakeholders. This makes it difficult to incorporate design principles for waste minimisation into software systems.

6 Waste Data Collection and Auditing Tools

A key challenge to the study of construction waste management is waste data deficiency [47]. Therefore, to tackle this challenge, a number of tools have been developed to provide means of logging the amount, type, and sources of waste generated in a building project. In turn, the data could be used to mitigate future waste generation, produce a benchmark for waste generation, forecast waste generation, or properly compute disposal charges. Examples of such tools include online waste control tool [48], waste management planning online tool [11], Calibre [49], Webfill [50] and ConstructClear [51].

In addition, the Building Research Establishment (BRE) developed SMARTStart [52], SMARTAudit [53], and True Cost of Waste Calculator [54], Site Methodology to Audit, Reduce and Target Waste (SMARTWaste) [47,55]. To sum up, waste data collection and auditing activities is primarily aimed at improving waste quantification. For this reason, the quality of the waste data must be ensured to guarantee the accuracy of waste quantification [56]. A major setback to this is that most of the construction waste are not segregated and are referred to as general waste.

21 Waste Prediction Tools

Waste prediction tools were developed to assist practitioners to estimate the expected waste
output of building projects. Examples of waste prediction tools include SMARTWaste [47,55],
Net Waste Tool (NWT) [57], Designing-out Waste Tool for Buildings (DoWT-B) [58], Webbased Construction Waste Estimation System (WCWES) [59], DeconRCM [60], and Demolition
and Renovation Waste Estimation (DRWE) tool [61].

The main contribution of these tools is the ability to estimate, at varying degree of accuracy, construction waste before they actually occur. They capture and analyse building design specifications to produce waste forecast with the identification of most appropriate construction materials and options. NWT and DoWT-B produce a more accurate estimation, yet, they could only be used after the bill of quantity has been produced and they are not compliant with BIM. Although DRWE is integrated with BIM, it is not actively employed during the design process. Therefore, engaging these tools within the design stages becomes important for real-time waste analysis and reduction.

6 Waste Quantification Models

7 The strength of waste prediction tools largely depends on mathematical and analytical waste 8 quantification models. The waste quantification models provide techniques to compute the 9 quantity of waste generated from building projects. Examples of waste quantification models 10 include Waste Index [12], Building Waste Assessment Score (BWAS) model [62], 11 Environmental Performance Score [63], Component-Global Indices [64], Stock-Flow model 12 [65], Spanish model [66], Material Flow Analysis model [67], and BIM-based deconstructability 13 assessment score [68].

However, majority of these models are based on aggregating waste indices and volumetric data in spite of the multi-dimensional nature of waste generation factors. As such, a major critique of these waste quantification models is that most of them were developed without adequate consideration for detailed material information and waste causative factors, therefore putting their reliability in question. Likewise, majority of the models are developed using location specific data therefore making them not universally applicable as the estimation could be influenced by project type, project location, project size, and construction methods [69].

21 GIS Tools

22 Geographic Information Systems (GIS) capture and analyse geographical information to provide 23 a visual representation for location-based services [70]. In fact, GIS integrated technology 24 provides a platform for many location-based services, which could be employed for enterprise 25 decision-making [71]. Examples of GIS tools for waste management include BREMap [72], 26 Global Position System (GPS) and GIS technology [73], and GIS-BIM based supply chain 27 management system [74]. A direct application of GIS tools in CDEW management is urban 28 mining [75]. Urban mining is concerned with the preservation of product information for the 29 purpose of end of life recovery of resources. To achieve this in the most effective way, GIS services could be used to locate the nearest recycling facilities. This will significantly reduce the
 energy required for the transportation of wastes and recyclables.

In spite of the availability of BIM based GIS tools [76–79] to capture different aspects of a construction project, none of them provides waste management functionality. A major setback to the implementation of such tools is interoperability between Architecture, Engineering, and Construction (AEC) and GIS standards.

From the review of all the construction waste management tools, a key underlying problem is that these tools are either too late at the design stage or not embedded within the design process, making it difficult for architects and design engineers to use the tools. The implication of this is that construction waste cannot be minimised by practising architects and design engineers using existing tools.

12 Methodology

13 The identification of the evaluation criteria and the development of the holistic BIM framework 14 are underpinned by theories of evaluation practice. Evaluation is a process of assessing the merit, 15 worth or significance of objects based on a set of criteria [80]. The objects could include services, 16 personnel, products, services, organisations, etc. According to Shadish et al. [81], the theories of 17 evaluation practices specify, in a systematic way, feasible approaches that could be adopted by 18 evaluators. In applying any of the available theories of evaluation practices, Davidson [82] 19 argued that it is important to start with a clear understanding of the purpose for which the 20 evaluation is carried out. According to Scriven [83], two purposes of evaluation exist, i.e., 21 summative and formative. Summative evaluation is carried out to pass judgement on something 22 while formative evaluation is a form of constructive assessment to improve the performance of 23 the evaluands. In this study, the evaluation of CDEW management was carried out towards a 24 formative purpose to identify shortcomings of existing tools in order to improve current and 25 future tools.

While the existence of several evaluation approaches is acknowledged, the current study takes a cue from Scriven's logic of evaluation [80], which starts by identifying the objects to be evaluated and proceeds to establish criteria for merit for the objects. Thereafter, the performance of the objects in relation to the criteria of merit must be determined before drawing valid conclusions. To achieve the objectives of this logic of evaluation, a social agenda approach, which favours constructivist evaluation [84] and qualitative methodology, was adopted. According to Bryson *et al.* [85], it is important to consider stakeholders' view and needs in a valid evaluation. Constructivist evaluation therefore allows the engagement of relevant stakeholders in obtaining an in-depth understanding of a phenomenon. The logic of constructivist evaluation practice employed in this study is enumerated below:

- 7 1) Determine the purpose of evaluation
- 8 2) Seek stakeholders involvement to build learning capacity and seek understanding from
 9 multiple perspectives
- 10 3) Identify list of evaluative criteria during stakeholders' engagement.
- 4) Organise list of evaluative criteria into common themes and choosing sources ofevidence.
- 13 5) Determine the performance merit of evaluands based on the evaluative criteria
- 14 6) Produce outcome of evaluation process

15 Based on the foregoing, a phenomenological study was carried out after a thorough review of extant literature on existing waste management tools (software and toolkits). Phenomenology 16 17 seeks to exhume common meaning and deep understanding from the experiences of several 18 individuals [86]. Van Manen [87] highlighted that phenomenology is carried out when researcher 19 is in active correspondence with the participants [88] and becomes interested in the stories of 20 others. The researcher therefore sets aside previous experience to obtain fresh perspectives about 21 the phenomenon under investigation. It is on this basis that phenomenology was chosen among 22 other research methodologies to examine detailed and deeper understanding of the criteria that 23 could be used to assess the performances of existing CDEW management tools based on expert 24 experiences. The phenomenological study involves Focus Group Interviews (FGIs) with 25 professionals within the top UK construction industry to determine a comprehensive list of evaluation criteria. Thereafter, the identified evaluation criteria were used to develop a holistic 26 27 BIM framework for construction waste management. These are discussed in the following 28 sections.

1 Focus Group Interviews (FGIs)

2 To ensure stakeholders participation in the determination of evaluative criteria for CDEW management tools, the study adopted qualitative Focus Group Interviews (FGIs). FGIs provide 3 4 the avenue to bring together real-life construction project team participants with the aim of 5 discussing different ways by which construction waste related issues are addressed. FGIs was 6 chosen for individual interviews with participants, since it allows participants to express their 7 personal opinions based on their experiences and allows them to build on responses by others. 8 Thus, helping to provide deeper insights into a wide range of perspectives within a short period 9 of time and confirming group thinking and shared beliefs.

10 After a thorough review of extant literature, 27 evaluation criteria that could be used to assess 11 the performance of existing CDEW management tools were identified. Accordingly, FGIs were 12 conducted to verify these evaluation criteria and to provide a wide access to a range of evaluation 13 criteria beyond those identified in the literature. In addition, the FGIs were conducted to provide 14 a forum to discuss the validity and applicability of the criteria before been used to develop a 15 holistic BIM framework for waste management. The FGIs would also help to identify the 16 perception and expectations of BIM and industry needs of construction waste management tools, 17 and to understand the role of BIM-based technologies in the adoption and implementation of 18 construction waste management strategies and tools. The FGIs were proactively moderated by 19 the research team to maintain openness and contributions from every member of each FGI.

20 Mays and Pope [89] noted that statistical representativeness is not the main requirement when 21 the focus of a study is to understand a social process. As such, the purpose of a focus group 22 research is not to establish a representative sample drawn from a population but rather to 23 identify specific groups of people who possess characteristics and experience of the 24 phenomenon being studied [90]. Accordingly, this study employs a critical sampling approach 25 where participants were chosen based on predefined criteria in order to ensure a deeper 26 understanding of the phenomenon [91]. Enforcing these criteria on the selection of participants 27 ensures that those with the right experiences are chosen to provide a logical generalisation of 28 experiences. Critical sampling method is a purposive approach to selecting a number of important cases in a phenomenological study. According to Creswell [86], using a critical 29 30 sampling in a phenomenological study helps researchers to drive genuine understanding of a 31 phenomenon and to isolate common meanings from personal experiences. This provides in1 depth exploration of a phenomenon based on a wide range of perspectives within a short period

No.	Team	Expectations/Themes	Number		
FGI-1	ArchitectsDesign EngineersDesign Managers	 Roles of designers in waste management. Design activities leading to waste. Design tools for waste management. 	6		
FGI-2	Project managersWaste managers	 Current waste management strategies Waste data monitoring and quantification techniques Waste data segregation approaches 	6		
FGI-3	Lean Practitioners	 Waste management techniques and practices from lean thinking Role of design in waste management 	6		
FGI-4	 Material suppliers 	 Roles of material suppliers in waste management. Waste from procurement activities. 	6		
		Total	24		

2 of time [92]. This group in critical sampling is usually small but produces the most important

3 information [93].

4

5 Accordingly, four FGIs were conducted with 24 participants in the following groups: designers, 6 project managers, lean practitioners, and material suppliers. Accordingly, the selection of 24 7 participants was based on the suggestion of Polkinghorne [94] who recommended that FGI 8 participants should not exceed 25. These groups of participants were selected due to their 9 responsibilities in mitigating waste generation and ensuring best practices for waste 10 management. The criteria for selecting participants include knowledge of CDEW management 11 (>10 years) and more than 15 year of experience the construction industry. In addition, the 12 participants were chosen randomly from UK construction companies that have completely or partially incorporated BIM into all their activities' stream. The distribution of participants is as 13 14 shown in Table 1.

15

Table 1: Outline of Participants for Focus Group Interviews

16

17 The discussions in each group were based on how the teams have employed tools in mitigating 18 construction waste in different projects. The participants were encouraged to discuss openly the

1 attributes that have been useful for effective construction waste prevention and reduction. 2 Interactions among the participants of the FGIs were recorded and later compared alongside all 3 the notes taken to ensure that all the important information was captured. Afterward, the 4 transcripts of the data were segmented for thematic analysis in order to compile a comprehensive 5 list of evaluation criteria. Particularly, the coding scheme was structured in a way to classify the 6 various waste management and technical related issues associated with software and toolkits 7 usage. During the FGIs, the participants were asked to discuss the technical and strategic 8 expectations of effective CDEW management tool. These expectations were then collated into a 9 set of evaluation criteria, which could be used to assess the effectiveness of existing and future 10 CDEW management tools. All the five categories of CDEW management tools and 27 evaluation 11 criteria identified from the literature were confirmed by the participants of the FGIs. In addition, 12 13 evaluation criteria were identified from the discussions of the participants.

13 Framework Development Methodology

14 In order to avoid the complexity of framework development [95], an architecture-driven 15 approach, which represents a collection of functional components and the description of the interactions amongst the components, was employed as proposed by Garlan and Shaw [96]. This 16 17 approach identifies the core and common components that are germane to the development of a 18 uniform and functional waste management system. As such, the integrity of the system is 19 maintained by avoiding unnecessary duplication and ensuring the reuse of standard components. 20 This also ensures that all components are loosely coupled [97] from each other to ensure 21 independence among components thereby encouraging their implementation one at a time. The 22 architecture driven approach also encourages the separation of data from algorithm, and from the 23 technology.

24 Analysis and Findings

In view of the aim of the study, a thematic analysis, which is an exploratory (content-driven) qualitative data analysis approach, was employed. Thematic analysis requires an exhaustive comparison of all transcripts' segments to examine the structure and relationships among themes. An exploratory approach was selected in favour of a confirmatory approach due to the lack of prior knowledge of the structure of evaluation criteria. In particular, thematic analysis allows the application of multiple theories across several epistemologies [98]. Therefore, it could be applied to research questions that go beyond an individual's experience [99] and allows for the emergence
of categories from data [100,101].

3 The thematic analysis process begins with familiarisation with the data by reading through the 4 transcripts several times in search of meanings, reoccurring patterns and repeating issues. The 5 initial coding employs descriptive terminologies used by participants' dialogue during the FGIs to increase dependability of the analysis as suggested by Guest et al. [99]. As such, the data was 6 7 reduced to categories by identifying similarities and patterns across the codes. Afterwards, a 8 thematic map was generated to provide an accurate representation of the transcripts. In order to 9 convey an accurate report of participants' experiences, attempts were made to analyse the 10 quotations beyond their surface meanings. This was done while ensuring the analytic claims are 11 preserved and are consistent with the quotations (from transcripts) as advised by Braun and 12 Clarke [98].

13 Results of the thematic analysis reveal a list of 40 criteria that could be used to evaluate the 14 performance of existing waste management tools and this was grouped under six categories, 15 which are: (a) waste prediction related criteria; (b) waste data related criteria; (c) commercial and 16 procurement; (d) BIM related criteria; (e) design related criteria; and (f) technological related 17 criteria. The evaluation criteria in each category are presented in the framework shown in Figure 18 3. To determine the performance merit of each tool, the 40 criteria were further used to evaluate 19 the 32 waste management tools identified from the literature shown as shown in Tables 2. This 20 is required as a major step in the logic of evaluation to benchmark the performance of the tools 21 before a logical conclusion could be drawn. The six groups of evaluation criteria are discussed 22 below.

23



2 Figure 3. A framework of criteria for evaluating the performance of waste management tools.

Evaluation Criteria		Π				Data Colle	ction and	Wast	e Pr	edicti	on Tool	s GIS	W	/M Q	uanti	ficati	on M	odels	V	VMP 1	emplates
						Audit '	Tools					Tools		-						and	Guides
	FGI-1	FGI-2	FGI-3	FGI-4 C-1-EE	Code frequency of criteria	 Waste Control Tool (Formoso, WMP Tool (McDonald and withner toox) CALIBRE (Chrysostomou, CALIBRE (Chrow et al., 2003) 	 ConstructClear (Rhuewise. SMARTStart (BRE, 2007) SMARTAudit (BRE, 2008) True Cost of Waste Calc. 	 SMARTWaste (Hobbs et al Net Waste Tool (WRAP, 2009) 	1) DoWT-B (WRAP, 2011c)	 CW Estimation Sys. (Li and Zhang, 2013) 	 DeconRCM (Banias et al., Demolition Waste Tool (Cheng and Ma, 2013) 	 S. BREMan (BRF. 2009) G. GPS-GIS Technology (Li et 7) GIS-BIM Supply Chain Sys. (frizarv et al. 2013) 	 Waste Index (Poon et al., 2001; RWAS (Fkanavake and Ofori FPS (Shen et al. 2005) 	 Component-Global Indices (Jalili, 2007) 	 Stock-Flow Model (Beragsdal et al., 2007) 	3) Spanish Model (Solis-Guzman <i>et al.</i> , 2009)	 Mat. Flow Analysis Model (Cochran and Townend. 2010) 	 Universal Waste Ratio (Llatas, 6) System Analysis Model (Wang 2014) 2014 	et al., 2014) 7) Cost Effective WMP (Mill et	 SWMP (WR AP. 2008) Material Logistic Plan (WR AP. Design out Waste Plan 	(WRAP, 2007; 2009) 1) Procurement Guide (WRAP. 2) Demolition Protocol (ICE, 2008)
Waste Prediction Related Cri	fer	าล				-0 64	5018	1	1	1	1 1	111	1-0	2	0	0	0	0 0	0	202	n n
Waste Prediction Related Criteria 1. Waste origin consideration 2. Waste causes identification 3. Waste prediction from design 4. Accurate waste estimation 5. Universal waste quantification model Waste Data Related Criteria 6. Interface for waste data collection 7. Transparency in data collection 8. Sufficient waste data 9. Accurate waste data 9. Accurate waste data 10. Segregated waste data 11. Accessible waste database 12. Universally applicable data				 ✓ ✓	21 2 6 9 4 6 7 11 6 8 7		~~~		>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>				~~~	· ~	~	~	✓ ✓	 			
13. Machine readable knowledge base	\checkmark		\checkmark	:	2												•	·			
BIM Related Criteria 14. BIM compliance* 15. Visualisation and reporting 16. Project lifecycle consideration 17. Design Centric consideration* 18. Collaboration among stakeholders* 19. Open standards support	$\begin{array}{c} \checkmark \checkmark$	$\langle \langle $	< < < < <<	1 2 1 √ 2 √ 2	16 20 19 24 22 8			~	~		 ✓ ✓ ✓ ✓ 	✓								`	/

 Table 2: Evaluation Criteria for Existing Waste Management Tools

Evaluation Criteria						Data Collection and		Waste Prediction	GIS Tools	WM Quantification Models	WMP Templates and Guides				
					_	Audit Tools		Tools			Guiues				
	FGI-1	FGI-2	FGI-3	FGI-4 Code frequency of criteria	3) Waste Control Tool (Formoso,	 WMP Tool (AcDonald and Smithers, 1998) CALIBRE (Chrysostomou, 2000) Webfill (Chen <i>et al.</i>, 2003) ConstructClear (Bluewise, 2010) SMARTStart (BRE, 2008) SMARTAudit (BRE, 2008) True Cost of Waste Calc. (BRE, 	1) IIUE CUST UI WASIE CAIC. (DNE,	 Nat RTWaste (Hohbs <i>et al</i>) Net Waste Tool (WRAP, 2009) DoWT-B (WRAP, 2011c) CW Estimation Sys. (Li and Theometry Ranias <i>et al.</i> 2011) Demolition Waste Tool (Cheng and Ma, 2013)) BREMap (BRE, 2009) (s) GPS-GIS Technology (Li et al., 2005) (noc.) (noc.) (noc.) (frizarry et al., 2013) 	 Waste Index (Poon et al., 2001; BWAS (Ekanayake and Ofori, ANAA EPS (Shen et al., 2005) Comnonent-Global Indices (Ialili. Stock-Flow Model (Beragsdal et Stock-Flow Model (Beragsdal et) Spañisti Model (Solis-Guzman et Anaar, Pooro, Universal Waste Ratio (Llatas,) Universal Waste Ratio (Llatas,) Universal Waste Ratio (Llatas,) 	 Cost Effective WMP (Mill et al., SWMP (WRAP, 2008) SWMP (WRAP, 2008) Material Locistic Plan (WRAP, Design out Waste Plan (WRAP, 2007; 2009) Procurement Guide (WRAP, Procurement Guide (WRAP, 				
					Э.	4 3 3 3 3 3 4 4 5 4 5 4 5 5 6 5 6 5 6 5 6 5 6 5 6 5	ť	44 44 44	444	51 52 52 55 51 55 55 55 55 55 55	55 67 67 67				
 Continercial and Producement F Cost Benefit Analysis Functionality* Supply chain engagement* Schedule integration Procurement process coordination Access to suppliers' database* Robust material database* Material Standardisation 	✓ ✓ ✓ ✓			14 22 5 12 17 19 16		~~ ~				~					
 28. Design out waste principles considerations 29. Automatic capture of design parameters* 30. Design optimisation* 31. Buildability consideration 32. Real-time design waste analysis* 33. Dimensional Coordination* 34. Design standardisation 35. Clash detection 	$\checkmark \checkmark \checkmark \checkmark \land \checkmark \checkmark \checkmark$	$\langle \langle \langle \langle \langle \langle \langle \langle \rangle \rangle \rangle \rangle \rangle \rangle \rangle = \langle \langle \langle \langle $	$\checkmark \checkmark $	26 8 6 15 13 18 16	5					~	~				
36. Decision support functionality* 37. Location based services 38. Cloud computing support 39. Application Programming Interface (API) 40. RFID support	 ✓ ✓ 	 ✓ ✓ ✓ ✓ ✓ 	√ \ √ \ √	15 6 2 2 3	j			\checkmark \checkmark	\checkmark						

Note: *Additional criteria identified from focus group interview

Waste Prediction Related Criteria

As previously noted, accurate waste quantification and prediction is a prerequisite for the implementation of effective waste minimisation strategies [66,102]. As such, waste prediction tools must be fully engaged during the design process to identify potential opportunities to reduce waste. However, no such tool exists as noted an architect during the FGIs:

"While it is possible to reduce waste during design, there is no tool that could measure waste that is preventable during the design process." (FGI-1)

Although existing tools such as NWT [57] and DoWT-B [58] require design parameters for waste forecast, they cannot be used until the design plan, or bill of quantity has been prepared. Thus, revealing a huge gap in knowledge that an operational waste management tool must provide waste prediction functionality during the model design process. This would be done with the knowledge that all building materials and strategies have waste potentials, which could be aggregated and analysed during design. A waste manager suggested that:

"The process could be like analysing design and then predicting the amount of waste it would generate. The calculation would be based on the fact that every material has defined waste potential. Once we know the volume of waste, then to reduce waste we could apply different strategies to design out waste, followed by ways to manage the unavoidable waste." (FGI-2)

This shows that an appraisal of the effectiveness of designing out waste strategies is important. As such, the participants of the FGIs agreed that a waste reduction ratio could be used as a measure of effectiveness of CDEW management tools, i.e.:

Waste Reduction Ratio = Reduced Waste / Original Waste

The scale runs from 0 to 1, such that a value of 0 depicts that noting has been reduced, while a value of 1 shows that all waste has been reduced.

Another setback to the use of waste prediction tools is the non-universality of quantification models. Most of the models depend on location/project-specific data influenced by project type, project location, project size, and construction methods [69]. To address this challenge, Llatas

[103] proposed a model, which estimates waste ratio using factors that depend on the construction technology, country, and project type; and a change in technology, country or project type only requires a modification of the corresponding factors. As a result, the model becomes universally applicable for waste quantification, thereby providing an avenue for the evaluation of alternative construction technologies across a number of project types in different locations.

Waste Data Related Criteria

A key challenge to the study of construction waste management is waste data deficiency [47]. To ensure the development of a robust waste prediction and minimisation tool, waste data collection and auditing as well as data analysis functionalities must be incorporated. This would ensure transparency and uniformity in data collection. The waste data must be stored in a centrally accessible database for ease of access. Ultimately, the result of the analysis of the data would provide a benchmark for waste generation of future projects. A major challenge of waste data collection is that most of the waste from a project is not segregated as claimed by an on-site waste manager:

"Most waste data recorded are for mixed/general waste, they are hardly segregated due to financial implications, time and space constraints. The waste is taken off by third party agents to waste recycling facilities. They may segregate the waste and may reuse or recycle it for their own purposes." (FGI-2)

So to ensure the accuracy of waste data, construction companies, and third party waste segregation companies must be appropriately engaged during the waste collection process. While discussing the impact of SWMP for transparent waste data collection, it was claimed that companies comply to retain their reputation and to fulfil legislative requirements as suggested by a project manager:

"SWMP is not actually to reduce waste, it is to monitor the amount of waste generated and how they are treated; apart from using SWMP to achieve BRE Environmental Assessment Methodology (BREEAM) point, it has no waste reduction tendency as it has not been used in the spirit for which it is meant; BREEAM has some sort of waste diversion target for which points are awarded." (FGI-2) To sum up, waste data collection and auditing activities are primarily aimed at improving waste quantification. For this reason, the quality of the waste data collected must be ensured to guarantee the accuracy of waste quantification [104]. In addition, such waste data must capture the expert knowledge required for waste quantification and designing out waste.

BIM Related Criteria

A common thread runs throughout the transcripts of the FGIs, which is the implicit and explicit references to BIM. Analysis of the transcripts shows that participants believe that BIM offers huge opportunities for construction waste management. Evidence from the interviews clearly shows that the integration of waste management and BIM is the way forward for an effective and economical waste quantification, waste prevention, collaboration amongst stakeholders and supply-chain integration. It was agreed among the designers in the focus group FGI-1 that:

"Gluing together the commercial, design, and procurement processes into a BIM software system to performing optimisation with little effort may provide more opportunities to see that it is economical to reduce waste in all the cases. This software would be a collaborative tool that would be used by all the stakeholders."

Ultimately, integrating waste management with BIM would favour the automatic capture of design parameter for analysis. This would help to mitigate errors, as a result of entering parameters manually as done in existing waste tools, in waste prediction. Integrating waste management will BIM thereby increases the useability of such tools in order to make appropriate decisions in favour of waste minimisation within BIM software. In addition, such system would offer leverage on existing BIM modelling platforms and material database to understand and visualise the effects of design decisions. Pointedly, BIM would provide a powerful collaboration platform for all stakeholders towards an effective construction waste management, seamless information sharing, and software interoperability. This would enable all stakeholders to participate actively in decision making, as noted by a design manager:

"To ensure effective collaboration, design has to be available in pictorial forms (3D) so that other members (non-designers/contractors) would easily understand it and use it for decision making." (FGI-2) Although DoWT-B [58] seems to be the most practical of all the existing tools in a sense that it could forecast the impact of design changes on waste output. However, it does not engage all stakeholders, and it is external to BIM software, thereby limiting its useability. The only BIM enabled waste management tool is Demolition and Renovation Waste Estimation (DRWE) tool [105], which leveraged on the BIM technology through the Autodesk Revit API. However, the system only estimates waste generation from demolition and renovation of existing buildings. This shows clearly the need for the development of a BIM-enabled tool for simulating the different aspects of waste reduction. Integrating waste management into BIM would also provide a powerful synergy, which would favour the simulation of other performances of buildings.

Commercial and Procurement Related Criteria

It was agreed that a synergy is required between design, commercial, and procurement for a successful waste management campaign and implementation. The reason for this is that some people/companies make money from waste; so blocking it in all directions may affect the business. As such, there is the need to understand the relationship between design and procurement as well as commercial and sustainability. In fact, it was affirmed that BIM provides the best opportunity to achieve this through improved coordination and communication among teams. One of the project manager suggested that:

"Currently, design is divorced from commercial and procurement. Synergy has to be ensured between finance department and procurement if any waste management strategy would be successful. And BIM is probably the most appropriate way to do this" (FGI-2)

This clearly shows that an efficient waste management strategy requires a tight supply-chain engagement [106]. This synergy would help to understand the financial implications of waste management and how waste output is influenced by procurement. In spite of the ability of some of the existing waste management tools to provide cost-benefit analysis functionalities, none of them is fully engaged during the procurement process. During the FGIs, it was noted that the procurement process contributes significantly to waste output but some procurement options favour waste reduction. A material supplier argued that:

"One of the economic strategy is to procure materials in bulk for the whole project, stock it at one of the project site, and then move it around on-demand. This is called doublehandling where more construction waste is generated due to material movement and manhandling, however, it is a cheap option. Contrary to this is just-in-time approach, where only the required materials are procured to generate lesser waste but it is a costly solution." (FGI-4)

This clearly shows that it is believed that waste reduction has a cost overhead. Likewise, it was argued that the generation of waste could be cheaper than avoiding waste especially when choosing between standard-sized materials and custom-sized materials. Custom-sized materials produce less waste but are costlier whereas standard-sized materials are cheap but generate construction waste through off-cuts. As a result, companies tend to give preference to lower cost over waste reduction in the procurement process. Although, the mind-set that waste reduction is costlier seems plausible at the procurement stage, however, it is defeated in the end by considering the environmental impacts of waste and the cost of waste disposal. Although some studies have explored the impacts of procurement processes on waste reduction [12,107], no study has been carried out to measure the financial impact of procurement in relation to waste reduction.

Design Related Criteria

While discussing the role of design in waste management and the availability of waste design tools, it was acknowledged that industry practitioners recognise the beneficial roles of design tools in waste reduction, however, it was confirmed that such tool does not exist. An architect claimed that:

"Although we are aware of waste reduction through design, but no software is available to simulate these waste reduction processes. Still, designing out waste is done manually and it requires design expertise knowledge and experience." (FGI-1)

This assertion was confirmed in the literature as none of the tools reviewed provide a real-time design-centric approach to waste minimisation. This clearly suggests that architects and design engineers take it upon themselves to identify possible sources of design waste through design optimisation. Three sources of design waste were identified as design changes, lack of dimensional coordination, and non-standardisation of materials. A design engineer argued that:

"Another way-out could be to optimise the design by keeping in mind the standardisation of materials to avoid off-cuts (often called design optimisation). It therefore means that most of the design waste is due to changes in the design, lack of dimensional coordination, and standardisation of materials." (FGI-1)

This affirms the general consensus in the literature that the largest percentage of construction waste could be avoided at planning and design (pre-construction) stages [10,15,39,102,108–110,16]. These evidences show that architects have huge responsibility to ensure that waste is given high priority, compared to project time and cost during design [12,111].

This therefore suggests the need for a design tool to identify possible sources of design waste and to assist in design optimisation. The focus of such design tools would be to capture and codify the knowledge about designing out waste and better understand the impacts of design strategies on waste output. Therefore, an important step in achieving this would be to create a list of basic parameters for designing out waste. In order to properly implement this, WRAP [44] identified 5 principles that must be considered. These principles are: (a) design for material optimisation, (b) design for waste efficient procurement, (c) design for reuse and recovery, (d) design for off-site construction, and (e) design for deconstruction and flexibility. Integrating these principles into design tools would foster real-time construction and end-of-life waste analysis and ensuring buildability of designs.

Technological Related Criteria

Based on the interview, it was pointed out that it is possible to integrate all the waste generation factors into design tools because every building project is unique. Even so, this might be a very complex task as observed by a lean practitioner:

"Waste management minimisation is a very complex issue; however, if what causes waste is known, then, they could be factored into waste management tools." (FGI-3)

For this reason, it is important for such tools to embrace intelligent technologies such as Decision Support Systems (DSS), big data analytics, machine learning, pattern recognition, etc. These technologies would empower waste minimisation tools with the ability to assist designers to understand and visualise the impact of design changes in real-time. Thus, supporting decisions

by providing recommendations for the choice of strategies and subsequently revealing avenue for significant waste reduction.

In addition, a robust waste management tool must be integrated with location-based technology such as GPS and GIS to provide location-specific services such as material tracking, supply chain management, and locating nearest waste management facilities. To ensure this, application schema such as Geographic Mark-Up Language (GML), cityGML, and IFC for GIS (IFG) must be supported to scale the hurdle of interoperability between AEC and GIS standards. Certainly, a full integration of GIS and BIM [112] into appropriate lifecycle stages of a project would assist in effective waste management [113].

Development of a Holistic BIM Framework for Waste Management

Taking into consideration the evaluation criteria identified from the literature and during the FGIs, a holistic BIM framework for a robust waste management system was developed as presented in Figure 4. This was done with the intention of integrating the industrial and technological requirements for waste management. The framework aims at achieving a holistic approach to design for waste minimisation by considering five design principles proposed by WRAP [44]. These design principles capture waste minimisation strategies at both the construction stages and end-of-life of the building.

The framework development employs an architecture-based layered approach, where related components are grouped into layers, to ensure hierarchical categorisation of components. This approach also clearly defines boundaries of stakeholders' responsibilities, supports fair and efficient allocation of resources, encourages independent implementation of components, and clearly defines components' interfaces for information exchange. A discussion of these layers is presented in successions with emphasis on how the components in each layer could be harnessed for construction waste management.



[Figure 3: Framework for a BIM-Based Construction Waste Management System]

Infrastructure Layer

The infrastructure layer is the first and bottom-most layer, which contains physical and virtual enterprise technologies, i.e., cloud computing, networking, hardware, and GIS technologies. Most importantly, this layer facilitates the transfer of the cost and management burdens from individual companies to the service providers due to the high financial requirement needed for setting up the infrastructure. As a result, this layer does not provide domain specific services as it creates the required platform for numerous specialty areas.

However, major challenges faced by service providers include security, ownership, and management issues. To scale the hurdles posed by these challenges, the infrastructure layer also provides the required security such as access control, intrusion prevention, Denial of Service (DoS) prevention, etc., scalable, and flexible billing and management models, and transparent user licences and agreements.

Data Layer

The data layer provides the shared knowledge, which uses decision making throughout the building's lifecycle. The layer provides centrally accessible databases, which could be remotely accessed in favour of efficient collaboration among stakeholders. For the purpose of waste management, this layer contains the universally applicable waste list and indices, which must be correctly mapped onto the material database and ontology for the purpose of waste data extraction from design models. In addition, the layer provides a knowledge base that captures design competencies required for efficient waste management. This knowledge base captures and codifies the knowledge about the five design principles proposed by WRAP [44] to better understand how the knowledge connects to waste output. An important component of this layer is the ontology database that captures the semantic relationship among other resources. This could be represented as a semantic network using Web Ontology Language (OWL), JavaScript Object Notation (JSON) or Resource Description Framework (RDF) schema.

The data layer also ensures the supply chain engagement by providing a database for suppliers and their related activities. As previously noted, the quality of construction waste quantification and prediction largely depends on the quality of data collected [66,102], as well as the quality of data representation and ease of knowledge extraction. As a result, the development of a robust waste prediction and minimisation tool must incorporate Waste Data Collection and Auditing functionality as well as Data Analysis features. This ensures a uniform standard for data collection, representation, and query. Ultimately, the result of the data analysis would provide a benchmark for waste generation for future projects.

Presentation Layer

For an effective implementation of BIM, all the team members must choose appropriate interoperable software tools [21]. Because of this, software and data interoperability becomes an issue of concern to ensure collaboration among stakeholders. Thus, BIM open standards were developed to represent and openly exchange BIM information. These standards include the IFC [24], Green Building XML [114] and the newer Construction Operations Building Information Exchange (CoBie) [115] for level 2 UK BIM adoption.

Therefore, the presentation layer defines the open BIM standards to ensure system interoperability and transparency in data exchange. This layer also contains spreadsheet formats for various forms of analysis of the performances of buildings, generic component models (OBJ, Material Library File – MTL, Polygon File Format – PLY, etc.), and software specific models (.rvt, .pln, .dng, etc.). Therefore, for a successful integration of waste management tools into BIM, such tools must incorporate exchange of data using these standard formats. However, there is a need to extend these standards to accommodate the concepts required for construction waste analysis.

BIM Business Domain Layer

The BIM business domain layer defines the core features of BIM as a set of concepts on top of the presentation, data, and infrastructure layers. This layer provides a platform for collaboration among stakeholders, document management, and seamless information sharing. This layer also provides a tight integration with CAD software for model visualisation and parametric modelling. In addition, the BIM business domain layer enables intelligent modelling by extending parametric properties of objects to capture numerous areas of the performances of buildings such as cost, scheduling, visibility, energy rating, etc.

The BIM business domain layer also helps to integrate the framework into the project's lifecycle. Admittedly, construction waste is produced at all stages of a building's lifecycle [116] especially at the construction and demolition stages [117]. Therefore, construction waste management tools must emphasise the integration of the entire lifecycle of a building [15,62] in favour of BIM adoption. BIM integration would enable waste management tools to consider waste from preparation stage to the end of life of the facility. However, conscious effort should be made to focus more on the pre-construction stages (0 - 4) where design changes are easier and cheaper.

Service Domain Layer

The service domain layer defines specific concepts and functionalities built on the BIM business domain layer to analyse and simulate various performances of a building project, particularly construction waste analysis and management. The waste management service domain contains the operational and supports technical requirements for designing out waste through BIM such as waste quantification, design model analysis, waste hierarchy consideration, waste prediction, reporting and visualisation functionalities.

Equally important, an effective design-based waste management system must provide recommendations for the choice of strategies and subsequently revealing avenue for significant waste reduction. These design-out-waste strategies include dimensional coordination, modular coordination, and standardisation in favour of off-site construction, deconstruction, and material recovery. Accordingly, the waste management service domain could be used with various BIM analysis software applications in other service domains to simulate a wide range of performance purposes. These software include Ecotect (thermal efficiency, lighting, visibility, solar shading, and exposure), Green Building Studio (CO₂ emission and energy consumption), and IES (airflow, sound, and acoustic quality).

Application Layer

The application layer is the sixth and topmost layer through which the various stakeholders access the specific domain services. This layer contains BIM software, which provides intelligent parametric modelling and n-D visualisation, web applications which provide access to the service domain through web interfaces, and mobile application, which provides access to the service domain on handheld devices like smart phones and tablets.

Since most BIM software, web, and mobile application provide Application Programming Interface (API) to extend their functionalities, it becomes important to harness this strength for rapid application development. API serves as building blocks for software applications thereby providing developers with the ability to customise application by leveraging on functionality of existing platforms. Available APIs include Revit .NET API, Vectorworks scripting language, ArchiCAD Geometric Description Language (GDL), etc. Several studies [105,118–121] have used the leverage of the Revit API [122] to simulate and analyse several aspects of BIM. Thus, this reveals the need to harness the strength of APIs for the development of waste management software.

Conclusion

Existing tools provide encouraging results for waste forecast and reduction at the design stages, however, the review of literature reveals that they are not holistic enough to tackle the challenges of waste management. As such, this study aims to investigate critical evaluation criteria for assessing the performance of existing waste management tools. After a thorough review of literature, 32 waste management tools were identified. These tools were validated with four FGIs leading to an emergence of 40 evaluation criteria. Analysis of the evaluated criteria includes thematic analysis to identify the structure and dimensions of the 40 evaluation criteria.

The results of the analysis reveal six categories criteria that could be employed to assess the performance of existing waste management tools. These include "waste prediction", "waste data", "BIM compliance", "design", "commercial and procurement", and "technological support". To incorporate these criteria, the industrial and technological requirements identified during the FGI were used to develop a holistic BIM framework for a robust waste management using an architecture-based layered approach. The BIM framework contains six layers, which are "application", "service domain", "BIM business domain", "presentation", "data", and "infrastructure". This thus contributes to waste management studies by organising relevant knowledge in a BIM framework to assist in the development of robust BIM tools.

The major contributions of this study are: (i) since existing construction waste management tools are too late during the design process, the study encourages construction waste management at the early design stage as compared to later stages when the waste has been generated; (ii) it provides a robust set of criteria to evaluate existing and future construction waste management tools; and (iii) the study provides a holistic approach and organises relevant knowledge required to tackle construction waste at the design stage effectively. The framework proposed in this study differs from other tools because the framework provides a holistic application architecture for

integrating BIM with construction waste management techniques leading to a BIM-based construction waste management tool. In addition, the BIM framework captures the technical and strategic expectation of a robust CDEW tool while addressing the shortcomings of existing tools. A major limitation of this study is that findings emanated from qualitative FGIs, as such, future studies should confirm the generalisability of the results using quantitative methods. Further areas of research also include developing tools based on the proposed BIM framework towards a framework-centred construction waste management systems. [66] [65] [64] [123].

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