Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills

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Abstract

The aim of this paper is to identify Critical Success Factors (CSF) needed for effective material recovery through Design for Deconstruction (DfD). The research approach employed in this paper is based on a sequential exploratory mixed method strategy. After a thorough review of literature and conducting four Focus Group Discussion (FGDs), 43 DfD factors were identified and put together in a questionnaire survey. Data analyses include Cronbach's alpha reliability analysis, mean testing using significance index, and exploratory factor analysis. The result of the factor analysis reveals that an underlying factor structure of five DfD factors groups that include '*stringent legislation and policy', 'deconstruction design process and competencies'*, '*design for material recovery'*, '*design for material reuse*, and '*design for building flexibility'*. These groups of DfD factor groups show that the requirements for DfD goes beyond technical competencies and that non-technical factors such as stringent legislation and policy and design process and competency for deconstruction are key in designing deconstructable buildings. Paying attention to the factors identified in all of these categories will help to tackle impediments that could hinder the effectiveness of DfD. The results of this study would help design and project managers to understand areas of possible improvement in employing DfD as a strategy for diverting waste from landfills.

Keywords*: Building deconstruction; design for deconstruction; end-of-life material recovery; sustainable construction; material reuse; critical success factors;*

1 Introduction

In recent times, the Architecture, Engineering, and Construction (AEC) industry has taken conscious effort to understand the concept of sustainable construction and to reduce the long-term effects of construction activities on the environment (Ajayi et al., 2015). This need requires that the usage and end of life impact of construction activities on the ecosystem are to be accessible at the design stage. In the same way, design activities must be beneficial to the ecosystem during building usage and end-of-life (Jrade and Jalaei, 2013; Oyedele and Tham, 2007). Owing to accrued economic benefits accruable from sustainable construction, the focus of AEC practitioners has shifted from the traditional methods of end-of-life building disposal to modern methods such as deconstruction. This is because design capabilities on reducing end-of-life impacts of building activities are limited in traditional methods of building disposal such as demolition and landfilling. It has also been argued that deconstruction, which is the disassembly of buildings piece by piece, allows the recovery of building materials and components after the end of life of buildings (Addis, 2008; Guy et al., 2006) in order to reduce waste through reuse (Crowther, 2005). Accordingly, deconstruction results in numerous benefits such as preservation of embodied energy, reduced carbon emission, reduced cost, reduced pollution, etc.

The paradigm shift from demolition to deconstruction is imperative because evidence shows that demolition generates up to 50% of the waste stream worldwide (Kibert, 2008). This volume of waste is about 18 million tonnes of waste in the UK alone. If this amount of waste is properly diverted from landfills, over £1.5 billion could be saved in terms of landfill tax and other costs. In addition to cost reduction, deconstruction eliminates potential health hazards and site disturbances caused by demolition. These aforementioned among others justify deconstruction over demolition as a strategy for economic and ecological sustainability. Despite the increasing awareness of deconstruction, little consideration has been given to Design for Deconstruction (DfD) due to lack of technical knowledge and supporting tools (Addis, 2008). In addition to the lack of tools, there is a general belief that the end-of-life of buildings may not occur for a long period (Guy et al., 2006). Understandably, the value of the building and its components after its end of life is not guaranteed, thus defeating the cost and purpose of ensuring deconstruction. Still, the current building methodology and material choice may become obsolete in decades considering the current trend in building and material engineering. Despite these challenges, the benefits of deconstruction outweigh the cost if the value of buildings components is retained after their end-of-life (Oyedele et al., 2013).

Despite efforts marshalled by all stakeholders in the AEC industry in mitigating Construction and Demolition Waste (CDW) and the evidence that deconstruction could drive waste minimisation initiatives (Akinade et al., 2015; Phillips et al., 2011), there has not been a progressive increase in the level of DfD. According to Dorsthorst and Kowalczyk (2002), less than 1% of existing buildings are fully demountable. Although the principles of DfD have been in practice for the past three decades, existing practices (Crowther, 2005; Guy, 2001; Kibert, 2003; Tingley, 2012) show that DfD is still far from reaching its waste minimisation potentials.

It is on this premise that this study seeks to explore and discuss critical success factors needed to ensure effective material recovery through DfD. Accordingly, the study will help to uncover functional requirements in maintaining a cost effective material recovery right from the design stages. After a review of extant literature in the research area of sustainable construction, construction waste reduction strategies, and modern methods of construction, an explorative qualitative study was conducted using Focus Group Discussions (FGDs). The purpose of the FGIs is to verify factors from the literature and to identify other factors that could influence DfD. Thereafter, 43 factors were identified and put together in a questionnaire survey. Data analyses include Cronbach's alpha reliability analysis, mean testing using significance index, and exploratory factor analysis. The results of this study bring to the fore the conditions that enable successful DfD and key factors that must be considered when designing deconstructable facilities. Pointedly, these factors will assist industry practitioners, such as design managers, project managers, architects, design engineers, etc., to understand the requirement for designing and constructing deconstructable facilities. In addition, the identified factors will form the basis for the development of tools for achieving sustainable construction.

The remaining sections of this paper are structured as follows: Section 2 contains a discussion of the concept of design for deconstruction and a review of critical success factors for building deconstruction. Sections 3 and 4 present a full discussion of the research methodology and data analyses process respectively. Then, a discussion on the identified groups of critical success factors is then presented in Section 5. The final part of the paper identifies contributions of the study to DfD and areas prompting further research.

2 Literature review: critical success factors for DfD projects

The traditional methods of building disposal require the dismantling and knocking down of buildings using crushing force using bulldozers, wrecking ball, explosives, etc. Although demolition offers a fast way of building disposal, its environmental and economic impacts are overwhelming. However, a more sustainable approach to the end-of-life disposal of buildings is building deconstruction, which is the disassembly of buildings piece by piece to maximise material reuse (Kibert, 2008). Accordingly, an efficient deconstruction procedure upholds the waste hierarchy by giving top priority to waste prevention through material reuse and recycling.

The goal of deconstruction is to eliminate demolition (Gorgolewski, 2006) and to ensure the recovery of components during usage or at the end-of-life of buildings (Kibert, 2008). Although there are concerns about the residual performances of building components after many decades of use, evidence shows that ensuring building deconstruction could result into beneficial results. For example, deconstruction efforts could stimulate rapid relocation of building, improved flexibility and retrofitting (Addis, 2008) while minimising the end of life impact of buildings (Kibert and Chini, 2000; Tinker and Burt, 2003). Apart from diverting demolition waste from landfills, deconstruction reduces site disturbance (Lassandro, 2003), health hazard (Chini and Acquaye, 2001) and preserves embodied energy (Thormark, 2001). Considering the potentials of deconstruction at diverting waste from landfills and the desire to achieve sustainable construction through design necessitates the understanding of how design could influence deconstruction.

Architects and design engineers must understand the purposes of DfD before its benefits can be maximised. According to Crowther (2005), the term DfD could serve multiple purposes, which include material recovery for building relocation, component reuse, material recycling and remanufacture. However, the tenets of DfD are more concerned with building relocation and component reuse rather than recycling or manufacturing. This viewpoint is because the recycling of building is now common practice in the construction industry. Understandably, a much more significant challenge is to design buildings that can be deconstructed and its components reused with minimal reprocessing.

With this view in mind, a review of extant literature in the area of modern methods of construction, design management, and project management, was carried out and three broad categories of DfD critical success factors were identified. These include: (i) material related factors, (ii) design related factors, and (iii) site workers related factors as shown in Figure 1. This section therefore presents a discussion of these three broad categories along with their associated factors.

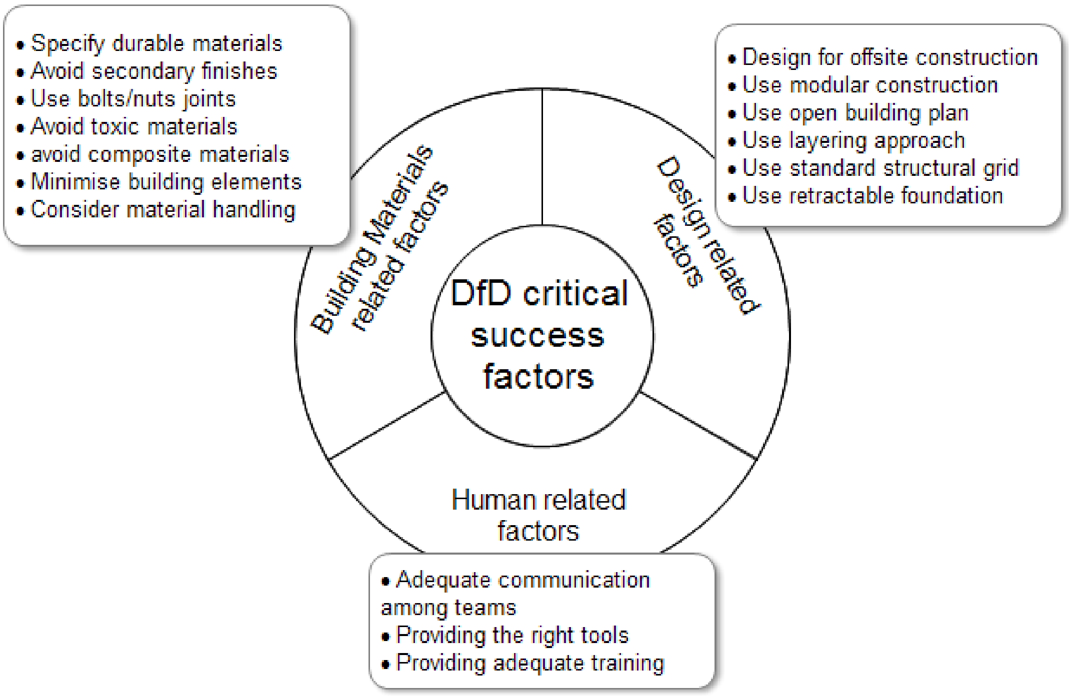

Figure 1: Design for deconstruction related factors

Table 1: Factors influencing design for deconstruction

No	Design for deconstruction factors	References
1.	Specify durable materials	(Tingley, 2012)
2.	Avoid secondary finishes	(Crowther, 2005; Guy and Ciarimboli, 2008)
3.	Use bolts/nuts joints	(Addis and Schouten, 2004; Akbarnezhad et al., 2014; Chini and Balachandran, 2002; Crowther, 2005; Gorgolewski, 2008; Guy et al., 2006; Webster and Costello, 2005)
4.	Avoid toxic materials	(Crowther, 2005; Guy et al., 2006)
5.	Avoid composite materials	(Crowther, 2005; Guy and Ciarimboli, 2008; Webster and Costello, 2005)
6.	Minimise building elements	(Chini and Balachandran, 2002; Crowther, 2005; Guy and Ciarimboli, 2008; Guy et al., 2006; Webster and Costello, 2005)
7.	Consider material handling	(Crowther, 2005; Davison and Tingley, 2011)
8.	Design for offsite construction	(Guy and Ciarimboli, 2008; Jaillon et al., 2009)
9.	Use modular construction	(Crowther, 2005; Davison and Tingley, 2011)
10.	Use open building plan	(Crowther, 2005; Davison and Tingley, 2011)
11.	Use layering approach	(Habraken and Teicher, 2000; Webster and Costello, 2005)
12.	Use standard structural grid	(Chini and Balachandran, 2002; Crowther, 2005; Webster and Costello, 2005)
13.	Use retractable foundation	(WRAP, 2009)
14.	Provide the right tools	(Chini and Bruening, 2003);
15.	Provide adequate training	(Chini and Bruening, 2003; Dorsthorst and Kowalczyk, 2002; Guy and Ciarimboli, 2008)

2.1 Design related factors

According to Warszawski (1999), design related factors cover commonly observed design principles and key performance indicators for DfD. Building design methodology encompasses approaches adopted by architects and engineers during building design to achieve desired forms and functions. Design methodologies thus help to understand design conceptual frameworks, which help to navigate the design process successfully. Meanwhile, the several criticism of conventional on-site construction methods shows that the use of Modern Methods of Construction – MMC (such as off-site construction, modular construction, open building system, etc.) offers significant benefits (Egan, 1998; Latham, 1994). Also, Pan *et al.* (2007) highlighted that MMC ensures cost and time certainty while improving building performances. In addition, MMC reduces on-site waste (Jaillon et al., 2009) and drives building deconstruction (Guy and Ciarimboli, 2008). Prefabrication alone, as an MMC, could reduce on-site waste up to 65% (Jaillon et al., 2009). Furthermore, the use of layer design approach facilitates building layout flexibility and retrofitting (Webster and Costello, 2005) and enables the recovery of building components. Other design methods in favour of DfD include using standard structural grid, using steel construction, using retractable foundations such as H-pile, etc.

2.2 Building materials related factors

Although DfD is not a new idea in the AEC industry, its planning is largely dependent on appropriate specification of building components to facilitate easy disassembly (Addis, 2008; Akbarnezhad et al., 2014). Accordingly, conscious effort should be made to specify durable materials (Tingley, 2012), use materials with no secondary finishes (Guy and Ciarimboli, 2008), use bolt/nuts joints instead of gluing (Chini and Balachandran, 2002; Webster and Costello, 2005), avoid toxic materials (Guy et al., 2006), and avoid composite materials (Crowther, 2005). Guy et al. (2006) also noted that the types and numbers of building materials, components and connectors must be minimised to simplify disassembly and sorting process. The use of recycled and reused materials is also encouraged (Crowther, 2005; Hobbs and Hurley, 2001) during design specification to broaden existing supply-demand chain for future deconstructed products. Evidence shows that reusing concrete components could reduce material cost by 56% (Charlson, 2008). Although selecting appropriate building components that facilitate deconstruction may increase the project cost, Billatos and Basaly (1997) suggest that architects and engineers must ensure that the cost of DfD is justifiable compared to cost of building demolition and disposal.

In addition to appropriate material selection, factors related to material handling play a major role in the success of a deconstruction process (Guy et al., 2006). Couto and Couto (2010) noted that handling of building materials and components is critical to knowing whether building components will be reused, recycled, or disposed. Material handling is important because deconstruction does not require expensive specialised equipment but a team of unskilled and skilled workers using basic tools (Kibert and Chini, 2000). In this regard, lightweight materials must be specified, components must be sized to suit handling (Crowther, 2005) and the means of handling component must be provided (Guy and Ciarimboli, 2008). This is to support handling operations during disassembly, transportation, and assembly. Although the breakage of building components, such as bolts and clips, are unavoidable during assembly and disassembly, spare parts and an on-site storage facility must be provided to replace broken or damaged components (Crowther, 2005).

2.3 Human related factors

In any construction related operation, a high level of commitment is required among all site workers to foster harmonious working relationship. This means that all participating teams must be willing to put forth considerable effort to actualise the overall aim of projects (Ajayi et al., 2016) . In addition, there must be clear, accurate, and regular communication among all these teams; and deconstruction takes no exception to these requirements for team-based environment. Deconstruction, been a labour-intensive systematic process, requires a team of site workers with basic skillsets. According to Kibert and Chini (2000), majority of building deconstruction processes are less technically advanced and do not require expensive heavy machinery. Accordingly, Chini and Bruening (2003) noted that providing the right tools and equipment during a deconstruction project will make the task easier and decrease damage to materials. However, the site workers must be properly trained to avoid poor craftsmanship and poor work ethics, and walked through the use of hand help tools, fasteners and materials.

3 Research methodology

After a review of extant literature, it became clear that a methodology that is exploratory in nature is needed for this study. Accordingly, a mixed methods approach was adopted to understand critical success factors for DfD. The mixed methods approach focuses on methods and techniques that work in obtaining a solution to a research problem (Onwuegbuzie and Leech, 2005). With emphasis, the researcher employs all available resources to understand the research problems by using pluralistic approaches to extract knowledge to the solution of the problem (Morgan, 2007). Therefore, the researcher is not constrained by a single system of reality. Mixed methods design gives the researcher the liberty to combine data collection and analysis methods from both quantitative and qualitative approaches to form a continuum. Accordingly, the sequential exploratory mixed methods was adopted to drive both in-depth understanding of the subject matter and generalise findings using a two-way research process (Creswell, 2014).

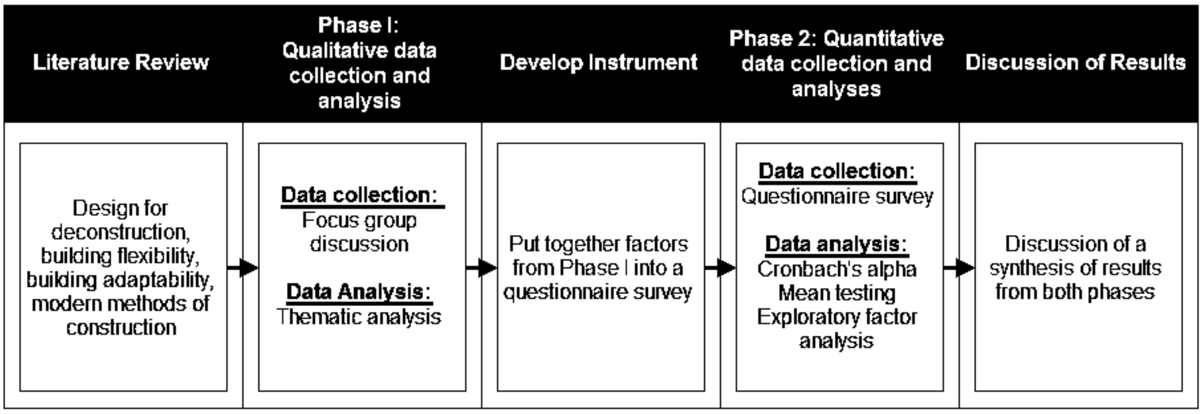

Figure 2: An overview of the sequential exploratory mixed method design process

The explorative sequential mixed methods process starts with a qualitative approach that allows for systemic reflection of experiences and inter-subjectivity of opinions in driving genuine understanding of actions (Gray, 2009). Creswell (2014) noted that this part of the process allows direct interaction with important stakeholders to understand what led to a phenomenon, to identify shortcomings in the current processes, and know how to improve the processes. In this study, FGDs is chosen over individual interviews as a qualitative data collection method to allow participants to build on others' responses (Neuman, 2009) and to provide an in-depth exploration of a wide range of perspectives within a short period of time (Gray, 2009). Accordingly, five FGDs were conducted with 24 participants based on the suggestion of

Polkinghorne (1989) that participants of FGDs must not exceed 25. The distribution of the participants is as shown in Table 2. To avoid dominant voices among the focus groups, the make-up of the five focus groups were relatively homogenous as advised by Smithson (2000). This is because participants with relatively similar backgrounds normally have similar perceptions and experiences about the same phenomenon. The discussions of the FGIs were recorded and later transcribed for data analyses to compile a comprehensive list of factors.

The list of factors compiled was then put together in a questionnaire survey and a pilot study was carried before sending the questionnaire out to a wider industry. The respondents for the pilot testing include five architects and two construction project managers with an average of 17 years of experience. The comment received was helpful to redefine and shorten some of the questions for the final questionnaire. The respondents of the final questionnaire were asked to indicate the importance of the factors on a five-point Likert scale, where 1 represents "*not important*" and 5 represents "*most important*". Another section was also included in the questionnaire, where the respondents could provide any necessary additional information.

Table 2: *Overview of the focus group participants*

	Categories of Participants	No of experts	Years of experience
FGD1	*Architects and Design Managers*	5	12 – 20
	• 3 design architects		
	• 1 site architects		
	• 1 design managers		
FGD2	*M&E Engineers*	5	9 – 22
	• 2 design engineers		
	• 3 site engineers		
FGD3	*Demolition Specialists*	4	10 – 15
FGD4	*Construction Project Managers*	5	12 – 22
FGD5	*Civil and Structural Engineers*	5	8 – 18
	• 2 design engineer		
	• 3 site based engineers		
	Total	24	

The distribution of the questionnaire survey was facilitated by a top UK construction company to ensure that the survey goes beyond their supply and to the wider industry players. In addition, practitioners from other big contractors were also contacted. This is to ensure that the speciality of the respondents exceeds a single building type. Accordingly, 130 industry practitioners were randomly selected for the questionnaire survey. The questionnaire survey was hosted using an online platform and a link was sent to each of the respondents. Table 3 shows the demographic distribution of the respondents of the questionnaire survey. Sixty-two (62) completed questionnaires were submitted, which represent a response rate of 47.7%. Three of the submitted questionnaires were discarded because of they were incomplete, thus leaving only 59 usable responses for analyses (45.4%). The average year of experience of the respondents in the construction industry is 14.5 years. The data from the responses was analysed using Statistical Package for Social Sciences (SPSS) software.

4 Data analyses and findings

Data analysis in a descriptive interpretivist research follows structured methods, which starts with the description of researchers' own experiences and followed by the description of textual and structural discussions of participants' experiences (Creswell, 2013). After a careful transcription of recorded FGI sessions, the interview transcripts were compared with notes taken to ensure that all important information and interactions during the FGIs were accurately captured. After which the transcripts of the data were segmented for thematic analysis using a framework approach (Furber, 2010). According to Braun and Clarke (2006), thematic analysis helps to identify main themes and sub-themes from qualitative data.

Table 3: Demographics of survey respondents

Variables	Sample size
Total questionnaire sent out	130
Total of submitted responses	62 (47.7%)
Discarded responses	2
Total number of usable responses	59 (45.4%)
Type of organisation	
Architectural	17
Contractor	20
Engineering consultancy	5
Waste management	10
Project management	7
Job title of respondents	
Architect	14
M&E engineer	7
Project manager	19
Civil/structural engineer	7
Lean practitioner	5
Design managers	7
Years of experience in construction industry	
0 – 5 years	6
6 - 10 years	10
11-15 years	20
16-20 years	13
20 - 25 years	6
Above 25 years	4

4.1 Coding scheme for thematic analysis

Thematic analysis was carried out using a coding scheme that was structured to classify the various issues associated with the concept of building deconstruction and critical success factors for DfD. The coding scheme has four classifications: discipline, context, keywords, and theme category. This coding scheme helps to identify dominant issues relating to DfD across the disciplines. Discipline coding classification shows the job role of the participant that provided a transcript segment. Context coding classification helps to understand the circumstances informing a transcript segment. The context coding classification include: (i) *New* – to signify when a new subject of discussion starts; (ii) *Response* – to signify a response to a question; (iii) *Build-up* – to signify when a contribution to an ongoing discussion is made; and (iv) *Moderator* – to mark a control segment provided by the moderator to control flow of discussion. Keyword coding classification depicts a summary of the main issue raised within a segment. This helps to identify prevalent issues and concerns across the transcript. The theme category shows the principal theme under which the issue discussed in the transcript segment falls. Example of quotation classification based on this coding scheme is shown in Table 4.

Table 4: Example of classification based on the coding scheme

No.	Quotation	Source	Discipline	Context	Keyword
1.	*"…designing for deconstruction is largely dependent on the competence of designers in picking the right building materials that are reusable"*	*FGD 1*	*Architect*	*Response*	*Specify materials that can be reused or recycled*
2.	*"structure building components according to their life span for effective maintenance work and deconstruction."*	*FGD 5*	*Structural engineer*	*Build-up*	*Structure building components according to their lifespan*

The results of the extant literature review and thematic analysis reveals forty-three (43) DfD factors that were put together into a questionnaire survey. The data analyses process for the responses of the questionnaire survey is presented in the next section.

4.2 Quantitative data analysis

To identify the critical success factors for DfD, a rigorous statistical process was employed. This includes reliability analysis, descriptive statistics using standard ratio of importance, and factor analysis. These statistical analyses techniques were selected because of the following reasons:

1) *Reliability analysis:* This is to statistically check if the 43 factors in the questionnaire consistently reflect the construct it is meant to measure.
2) *Descriptive statistics using standard ratio of importance:* Mean ranking will be used to identify the top five critical success factor.
3) *Factor analysis:* This will help to identify clusters of factors that measure aspects of the same underlying dimension.

4.2.1 Reliability analysis

Reliability analysis was carried out to determine the internal consistency of the factors in the questionnaire. This is to confirm whether the factors and their associated Likert scale are actually measuring what they were intended to measure (Field, 2005). Accordingly, Cronbach's alpha coefficient of reliability (α) was calculated for the factors using Equation (1).

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

Where N is the total number of factors; $\overline{COV}$ is the average covariance between factors; S_i^2 and COV_i are the variance and covariance of factor 'i' respectively. According to Field (2005), the Cronbach's α has a value from 0 to 1 and the higher the reliability coefficient, the greater the internal consistency of the data. It is generally suggested that a value of α = 0.7 is acceptable and α> 0.8 depicts good internal consistency. For this study, the calculated α is 0.903, which demonstrates a very good reliability and internal consistency of majority of the data. To confirm that all the factors are contributing to the internal consistency of the data, the "*Cronbach's alpha if item deleted*" of each factor was examined as shown in Table 5. According to Field (2005), if the "*Cronbach' alpha if item deleted*" for a factor is higher than the overall coefficient, the factor could be deleted to improve the overall reliability of the data. Based on this, five factors, i.e., design components sized for transportation, design consideration of crane movement during design, use of dry wall system such as drywall partitions and wall lining, availability of pre-cut materials in standard dimensions, and design consideration for on-site vertical and horizontal movement of components were deleted. The remaining 38 factors were then subjected to ranking using the significance index.

4.2.2 Comparison of factors using standardized ratio

After establishing the reliability of the data, it is essential to measure the level of the significance of the respondents' perception of each DfD factor. Accordingly, a significance index was computed using Equation (2). This equation is based on the formula computed by Chan and Kumaraswamy (2002) and Oyedele (Oyedele, 2013). The significance index is given as:

$$Sig.index = \left(\frac{\sum_{i=1}^{N}(S_i)}{NS}\right) \times 100\% \qquad (2)$$

Table 5: Reliability analysis of factors influencing design for deconstruction

	Design for deconstruction factors	Cronbach's α if item deleted	Sig. index	Overall rank
1	Award of more points for building deconstructability in sustainability appraisal	0.905	93.90	1
2	Legislation to make deconstruction plan compulsory at the planning permission stage	0.905	92.54	2
3	Improved education of professionals on design for building deconstruction	0.904	90.85	3
4	Government legislation to set target for material recovery and reuse.	0.904	90.51	4
5	Early involvement of demolition and deconstruction professionals during design stage	0.905	90.17	5
6	Effective communication of disassembly needs to other project participants	0.904	89.83	6
7	Use bolted joints instead of chemical joints such as gluing and nail joints	0.903	89.49	7
8	Specify building materials and components with long life span	0.906	89.15	8
9	Specify materials that can be reused or recycled	0.903	89.15	8
10	Production of a site waste management plan	0.905	89.15	8
11	Project contractual clauses that will favour building material recovery and reuse	0.906	88.14	11
12	The use of BIM to simulate the process and sequence of building disassembly	0.902	87.80	12
14	Knowledge of end-of-life performances of building materials	0.905	87.46	14
13	Avoid toxic and hazardous materials during design specification	0.903	87.12	13
15	The use of BIM to estimate end-of-life property of materials	0.903	87.12	15
16	Structure building components according to their lifespan	0.904	86.78	16
17	Design foundations to be retractable from ground	0.904	86.10	17
18	Separate building structure from the cladding	0.905	86.10	17
19	Use joints and connectors that can withstand repeated use	0.904	86.10	17
20	Avoid specifying materials with secondary finishes	0.904	84.75	20
21	Design for steel construction	0.904	84.75	20
22	Avoid composite materials during design specification	0.903	83.73	20
23	Design conformance to codes and standards	0.903	83.39	23
24	Ensure dimensional coordination of building components	0.903	83.39	23
25	Design for modular construction	0.906	82.03	25
26	Design for preassembled components	0.903	82.03	25
27	Use standard structural grid	0.904	81.69	27
28	Making inseparable products from the same material	0.905	80.68	28
29	Using interchangeable building components	0.902	80.68	28
30	Effective pre-design disassembly review meetings	0.904	80.00	30
31	Production of COBie to retain information of the building components	0.905	79.66	31
32	Specify lightweight materials and components	0.905	79.32	32
33	Use open building system for flexible space management	0.906	79.32	32
34	Minimise the number of components and connectors	0.904	78.98	34
35	Minimise the types of components and connectors	0.902	78.64	35

36	Design for the repetition of similar building components	0.903	77.97	36
37	Preparation of a deconstruction plan	0.905	77.97	36
38	Standardising building form and layout	0.906	77.97	36

Overall Cronbach's alpha is 0.906,
Significant at 95% confidence Interval=0.05

Where S_i is the significance of the i^{th} respondent with values from 1 to 5; S is the highest possible severity rating, i.e. 5; N is the total number of respondents. The significance index of and the overall ranking of each factors is as shown in Table 5. From the ranking, the top five factors are (a) improved education of professionals on design for building deconstruction; (b) award of more points for building deconstructability in sustainability appraisal; (c) legislation to make deconstruction plan compulsory at the planning permission stage; (d) government legislation to set target for material recovery and reuse; and (e) early involvement of demolition and deconstruction professionals during design stage.

The emergence of these top factors confirms the place of government legislation, appropriate education, and early supply chain integration in achieving effective DfD.

The government has a major role to play in the use of DfD as a strategy for sustainable construction. First, the government must set targets for building deconstruction and must provide supporting legislation to drive such targets. The stringency of these targets in driving the national and global sustainability agenda has been a proven way of ensuring the compliance among the practitioners in the construction industry. Although the benefits of DfD are well explored across literature (Akinade et al., 2015; Crowther, 2005; Davison and Tingley, 2011; Guy et al., 2006; Kibert, 2003), little effort has been made to propagate this knowledge to industry practitioners. Pointedly, architects and design engineers should be sensitised about the environmental benefits of design for building deconstruction. In line with this recommendation, early involvement of demolition and deconstruction experts must be ensured at the early design stages. This will allow the demolition and deconstruction experts to contribute their end-of-life expertise knowledge and experience during the design stage in order to achieve higher end-of-life building performance.

4.2.3 Exploratory factor analysis

The aim of the exploratory factor analysis is to identify the underlying dimension of the factors identified from the reliability analysis. This is done to replace the entire dataset with a smaller number of uncorrelated principal factors. A principal components analysis (PCA) was carried out on the 41 factors with orthogonal rotation (varimax) on the SPSS software. The Kaiser-Meyer-Olkin (KMO) value and the Bartlett tests of sphericity were 0.521 (above 0.5) and 7.8e-57 (less than 0.5) respectively. These values show that the data is suitable for factor analysis. Accordingly, Principal Component Analysis (PCA) was used as factor extraction and varimax rotation was used as factor rotation. During this process, all values with Eigen value of 1.0 were retained, and factors with factor loading of 0.4 were selected as part of factor grouping. The results reveal a five group of factors, which account for 69.01% of the total variance as shown in Table 6. The grouping was interpreted and labelled based on the factors assigned to the group. The DfD factor groups include: (a) group 1 denotes *stringent legislation and policy,* (b) group 2 denotes *design process and competency for deconstruction*, (c) group 3 denotes *design for material recovery*, (d) group 4 denotes *design for material reuse*, and (5) group 5 denotes *design for building flexibility*

Table 6: Component labelling and corresponding criteria from exploratory factor analysis

	Eigen value	% of variance	Factor loading	% weight within group	% norm. weight
1. Stringent legislation and policy	9.53	27.02			39.15
Award of more points for building deconstructability in sustainability appraisal			0.65	26.86	10.52
Government legislation to set target for material recovery and reuse			0.64	26.45	10.36
Project contractual clauses that will favour building material recovery and reuse			0.54	22.31	8.73
Legislation to make deconstruction plan compulsory at the planning permission stage			0.59	24.38	9.54
2. Deconstruction design process and competencies	3.64	12.64			18.32
Improved education of professionals on design for building deconstruction			0.47	7.24	1.33
Effective communication of disassembly needs to other project participants			0.52	8.01	1.47
Effective pre-design disassembly review meetings			0.61	9.4	1.72
Design conformance to codes and standards for deconstruction			0.65	10.02	1.84
Early involvement of demolition and deconstruction professionals during design stage			0.59	9.09	1.67
Production of a site waste management plan			0.83	12.79	2.34
The use of BIM to estimate end-of-life property of materials			0.66	10.17	1.86
Preparation of a deconstruction plan			0.79	12.17	2.23
The use of BIM to simulate the process and sequence of building disassembly			0.94	14.48	2.65
Production of COBie to retain information of the building components			0.43	6.63	1.21
3. Design for material recovery	2.85	10.73			15.55
Use bolted joints instead of chemical joints such as gluing and nail joints			0.77	15.4	2.39
Avoid composite materials during design specification			0.82	16.4	2.55
Design foundations to be retractable from ground			0.70	14.00	2.18
Specify building materials and components with long life span			0.67	13.40	2.08
Specify lightweight materials and components			0.49	9.80	1.52
Use joints and connectors that can withstand repeated use			0.47	9.40	1.46
Minimise the number of components and connectors			0.43	8.60	1.34
Minimise the types of components and connectors			0.65	13.00	2.02
4. Design for material reuse	2.42	9.67			14.01
Knowledge of end-of-life performances of building materials			0.77	23.62	3.31
Avoid toxic and hazardous materials during design specification			0.43	13.19	1.85
Making inseparable products from the same material			0.67	20.55	2.88
Avoid specifying materials with secondary finishes			0.41	12.58	1.76

Specify materials that can be reused or recycled			0.52	15.95	2.23
Design for steel construction			0.46	14.11	1.98
5. Design for building flexibility	2.12	8.95			12.97
Use open building system for flexible space management			0.78	12.44	1.61
Using of interchangeable building components			0.77	12.28	1.59
Design for modular construction			0.51	8.13	1.05
Design for preassembled components			0.50	7.97	1.03
Design for the repetition of similar building components			0.54	8.61	1.12
Ensure dimensional coordination of building components			0.68	10.85	1.41
Separate building structure from the cladding			0.72	11.48	1.49
Standardising building form and layout			0.47	7.50	0.97
Use standard structural grid			0.63	10.05	1.30
Structure building components according to their lifespan			0.67	10.69	1.39
		69.01			

5 Discussions

Keeping in mind that this study is based on a mixed methods strategy, each of the DfD factors is further discussed based on the results of both qualitative and quantitative data analyses. In addition, this section discusses possible ways of maximising the resultant effects of the factors on DfD.

5.1 Stringent legislation and policy

Stringent legislation and policy, which accounts for the highest variance of 27.02%, is ranked as the most significant success factor for DfD. This is not surprising since several studies (Ajayi et al., 2015; Lu and Yuan, 2010; Oyedele et al., 2014) suggest that the government has a major role to play in the current national and global sustainability agenda. First, the government must set targets for building deconstruction and must provide supporting legislations and policies to drive such targets. The stringency of these legislations and policies has been a proven way of ensuring the compliance among the practitioners in the construction industry. This is because building construction works require planning approval and the authorisation must be given within the legislative framework of building regulations. For example, the UK government has made the provision of Code for Sustainable Homes (CfSH) compulsory for all residential building construction. In addition, the use of Site Waste Management Plan was a compulsory requirement in the UK for clients and principal contractors for building projects that is over £300,000 (WRAP, 2008). Although the use of SWMP is no longer compulsory in England since December 2013, it provided the construction industry with a sense of environmental responsibility towards effective waste management before it was generated.

As noted by Häkkinen and Belloni (2011), several clients, especially government parastatals and large companies, are setting targets for waste diversion and building disassemblage in construction contracts to demonstrate that their buildings are sustainable. This is to show their environmental responsibility to reduce global warming, preserve the limited natural resources and comply with government policies. This is evidenced through the commitment of project teams to obtaining high building sustainability scores on existing standards like BREEAM, LEED, CASBEE, BEPAC, Eco-Quantum, CfSH, etc. (Schweber, 2013; USGB, 2005). Achieving this success provides clients with the assurance that their projects are setting the highest standards within the industry. In this way, building deconstruction should be included as part of building sustainability assessment scoring systems and assigned a high point.

Although C&D waste is highly regulated in the United Kingdom and the benefits of building deconstruction is well known (WRAP, 2009), there are not stringent legislation and policies that place obligation on clients and contractors to build deconstructable facilities. As rightly noted by a participant from FGI1 imbibing building deconstruction in the industry will be difficult unless it is driven by legislation. At this point, the question is: why will someone concentrate on DfD when there is the moral and professional responsibility of designing for construction? The targets of the stringency of building deconstruction therefore should include appropriate legislation and policies to ensure wide acceptance and compliance among practitioners. In addition, the requirements and terms for building deconstruction and material reuse must be clearly specified in the project contracts.

5.2 Deconstruction design process and competencies

This group produced a total variance of 12.64% and comprised ten sub-factors. A careful consideration of the nine factors revealed that the term 'd*esign process and competency for deconstruction'* aligns with the composition of this group. The definition of design process management, within this context, matches the definition of Sinclair (2011) who defined it as "the discipline of planning, organising and managing the design process to bring about the successful completion of specific project goals and objectives". This definition is key because the emergence of a good design is as a result of a well-managed process (Bruce and Bessant, 2002), which requires both specialised and organisational skills (Chiva and Alegre, 2007). Despite the existence of establish standard procedures for building designs, it is surprising that the construction industry has shown little interest in defining widely acceptable procedures and tools aimed at improving the efficiency of DfD.

Due to the increasing sophistication of buildings, the need for more information for the purpose of construction, building operation and maintenance has become vital (Jordani, 2010). This information is important for tracking building construction processes and performance, isolating inefficiencies in building operations, and responding to specific needs of clients (Bilal et al., 2016a). Evidence shows that design quality and design documentation form an important requirement for successful building construction and facility management (Andi and Minato, 2003; Gann et al., 2003). Accordingly, COBie document must be produced to retain information about building components. Many studies have stated that deconstruction has not been a popular end of life option due to lack of adequate information and uncertainties about future technologies. This is because after a report of hazardous materials and historical features is obtained, the demolition contractor applies for a demolition permit and proceeds with other activities such as waste management planning and meeting BREEAM requirements. A major challenge at this point is that it is difficult to know which of the components are reusable or recyclable. However, the process of identifying hazardous materials and reusable components could be easier if these materials are well documented in the building design and manuals.

Notably, the ease of designing deconstructable buildings relies on the appropriate use of technologies and their effective integration into the design process. Goedert and Meadati (2008) illustrated that BIM has capabilities to capture building design and construction process documentation to provide full inventory of components and to sustain the relevant information. In fact, the use of BIM on construction projects has enabled practitioners to embed relevant facility maintenance into building models (Akinade et al., in press). This information could also assist demolition contractors in identifying building components that could be recovered for recycling or reuse. It is general knowledge that most of existing buildings were not built to be deconstructed (Jaillon and Poon, 2014), thus making it difficult to understand the process of deconstructing them (Chini and Balachandran, 2002). Accordingly, necessary information such as deconstruction plan must be provided and integrated with BIM to simulate the assembly and disassembly process. In addition to having a deconstruction plan, DMCP (2013) identified a checklist of other documents that are important for acceptable site practice during deconstruction. These documents include site information sheet, environmental management plan, complain/incidence logbook, traffic management plan, noise/vibration monitoring report, etc. In addition, setting up a design stage waste management plan to record the avenues to minimise construction waste and their associated actions are also beneficial.

From the foregoing, improved education on DfD must be provided for architects and design engineers. Areas of training should include design process for designing deconstructable buildings, code for acceptable DfD, design documentation for DfD, use of BIM-based software and other tools for DfD, design for effective material handling, design for safe disassembly, etc.

5.3 Design for material recovery

With a variance of 10.73% and eight DfD sub-factors, this group contains factors related to selecting appropriate building components for eventual material recovery. This percentage of variance reveals that despite the relevance of core competencies in designing deconstructable facilities, the first two groups that are strategic in nature are key to enabling successful DfD. This is because technical skills for DfD are not scarce, but strategic requirements for DfD has not been well developed. Several studies (Akinade et al., 2015; Davison and Tingley, 2011; Densley Tingley and Davison, 2012) show that architects and design engineers seeking to incorporate deconstructability into their designs must give adequate attention to the selection of building materials, components, and connectors from the early phase of design. The participants of the FGD also reiterated the importance of choosing the right building components during design and the consensus among the participants of the FGDs is that reusable components without secondary finishing must be specified, the types of building components must be minimised, and the use of nut/bolt joints must be encouraged in place of nails and gluing. Considering these factors during DfD would favour the recovery of building components without the generation of waste, the reuse of building components without reprocessing, and the preservation of resources.

In addition to this, literature (Crowther, 2005; Guy et al., 2006; Pulaski et al., 2003) brings to light the fact that considering the following factors is beneficial to building deconstructability: specifying easily separable materials/components, using joints and connectors that can withstand repeated use, using retractable foundations (such as H-pile), avoiding composite materials during design specification, and specifying lightweight materials. However, existing literature shows that specifying the right materials for DfD could have immense financial implications on the project (Billatos and Basaly, 1997). It is thus imperative that the costs of DfD and the actual deconstruction do not exceed the cost of demolition and waste disposal. This suggestion reveals that there is a need for strategic justification for DfD beyond the environmental requirements. Accordingly, continued justification must be provided for the cost effectiveness of DfD as a sustainable approach.

5.4 Design for material reuse

This group represents 9.67% of the total variance and it contains six DfD sub-factors. The need for reusability of materials after deconstruction stresses the need for the design team to bring to the fore their knowledge of the end-of-life performance of building materials (Bilal et al., 2016b). This is because if the building methodology supports material recovery but the materials are not reusable, then the purpose of DfD is defeated. Accordingly, preference must be given to durable materials and materials that can be reused or recycled. Materials without secondary finishes must also be specified to increase the chance of material reuse. From the foregoing, we see that design for steel construction is an ideal strategy for ensuring building deconstructability. This is because steel can be reused repeatedly and can be cut, shaped or joined with ease. When compared to other ferrous metals, steel has high recycling potential with minimal embodied energy and waste production. It has been shown that up to 100% of recovered steel from demolition projects can be reused or recycled without loss of quality or performance (Coventry et al., 1999) and that there is ready market for reclaimed steel. Apart from steel, other materials that could be used in deconstructable buildings include timber, prefabricated concrete components, aluminium, glass, etc.

According to Crowther (2005), proper handling of building material plays a major role in DfD in determining whether the components are reusable, recyclable, or marketable. Coelho and de Brito (2012) highlighted that material handling is key because the use of heavy equipment is not suited for component-by-component assembly/disassembly of building. Design consideration for material handling is therefore necessary during DfD to avoid damage to material and health hazard. Therefore, toxic materials (such as asbestos), that could pose health concerns during deconstruction, must be avoided as suggested by Crowther (2005) and Guy et al. (2006).

5.5 Design for building flexibility

This group constitute 8.95% of the total variance and contains ten sub-factors. It is common practice to alter the use and form of buildings throughout its lifetime to meet the needs of users. During such practice, building must go through series of component replacement, maintenance, and retrofitting. Design for building flexibility therefore enables significant changes to be made to buildings during usage to meet future uncertainties without the need to reconstruct the whole building. Evidence from the literature shows that design for MMC are key contributors to building flexibility. Several flexible and adaptable buildings have been constructed using MMCs such as prefabrication and modular construction. Pointedly, the mutual relationship between MMC and deconstruction could leverage prefabricated and modular assemblies to be recovered as a whole without generating waste. The following are also key consideration while designing flexible buildings: use of open building system for flexible space plan management, using interchangeable building components, separating building structure from cladding, standardizing building form and layout, use of standard structural grid, ensuring dimensional coordination of building components, and the repetition of similar building components.

Guy (2006) argued that design for building flexibility requires in-depth conceptualisation of the make-up of building systems to understand the intertwined complexity and interaction among building components. This thinking is based on the hierarchical shearing layer of change proposed by Brand (1994), which structures building components according to their rate of change and life expectancy. These layers include stuff, space plan, services, skin, structure, and site. The main advantage of the layering system is that building components can be modified within a layer without affecting other layers.

6 Conclusion

This study examines the critical success factors for DfD from the perspective of industry experts who are involved in demolition and deconstruction projects. This is to articulate conditions that enable successful DfD by their direct or indirect effects on the eventual recovery of building materials. Using a mixed methods strategy, this paper provides a structured account of an in-depth exploration as well as empirical investigation of the unique factors influencing effective DfD. After conducting five FGDs, 47 DfD factors were put in a questionnaire survey and sent out to 130 industry practitioners with a return rate of 47.7%. The responses of the questionnaire survey were then subjected to reliability analysis using Cronbach’s alpha, mean testing and exploratory factor analysis. Accordingly, a PCA was conducted with orthogonal varimax rotation. The result of the PCA reveals five groups of DfD factors were identified, which include ‘stringent legislation and policy’, ‘design process and competency for deconstruction’, ‘design for material recovery’, ‘ design for material reuse, and ‘design for building flexibility’.

One of the major contributions of this study is that DfD should be given more points in key sustainability guidelines e.g. BREEAM, LEED, CfSH, etc. in order to compel practitioners to use DfD. In addition, the competency of designers should be improved through sustainability education for designers and making DfD as part of the curriculum of professional bodies (such as CIOB, RIBA, ICE). In addition, these bodies should organise CPD courses where deconstruction process is explained and competency is enhanced in order for practitioners to inculcate DfD practices. It is also important that demolition engineers be brought on board during the design process through early involvement of demolition contractors and engineers.

Observably, the results of this study have immense implications on both research and industrial practices towards achieving the current sustainability agenda of the construction industry. First, the study brings to the fore the consideration of key factors that must be considered when designing deconstructable facilities. Second, the grouping of these factors could be used by design managers, project managers, architects, and design engineers as a guide for designing and constructing buildings that could be deconstructed. This will also assist industry practitioners to know key factors that could be incorporated into artefacts such as software for achieving sustainable construction. Although DfD does not suffice to address the entire sustainability goals, it reduces the need for new building materials, prevents the generation of CDW, and preserves the embodied energy of building materials.

Despite the contributions of this study, there are certain limitations. First, the participants of the FGDs and the respondents of the questionnaire survey were drawn from the UK construction industry and the findings should be interpreted within this context. Another limitation is that this study only focused on design team factors related to DfD. Future studies can examine other factors such as organisational and project factors related DfD. An additional future research direction that seems most promising at this stage is to understand the linkage between building deconstruction and project cost. Accordingly, further empirical studies are required to know how the critical success factors identified in this study can influence the costs of building design and project execution. Achieving this will help in carrying out a sound economic evaluation of the building projects while seeking to leverage the benefits of building deconstruction. Although building deconstruction may be the most beneficial consideration for an end-of-life scenario, it may not be the most economical. This is because deconstruction costs could be 17%-25% higher than the demolition cost (Dantata et al., 2005; Akinade et al. 2015).

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