Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS)

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Waste Minimisation through Deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS)

Abstract

The overall aim of this study is to develop a Building Information Modelling based Deconstructability Assessment Score (BIM-DAS) for determining the extent to which a building could be deconstructed right from the design stage. To achieve this, a review of extant literature was carried out to identify critical design principles influencing effectual building deconstruction and key features for assessing the performance of Design for Deconstruction (DfD). Thereafter, these key features were used to develop BIM-DAS using mathematical modelling approach based on efficient material requirement planning. BIM-DAS was later tested using case study design and the results show that the major contributing factors to DfD are use of prefabricated assemblies and demountable connections. The results of the evaluation demonstrate the practicality of BIM-DAS as an indicator to measure the deconstructability of building designs. This could provide a design requirement benchmark for effective building deconstruction. This research work will benefit all stakeholders in the construction industry especially those interested in designing for deconstruction. The eventual incorporation of BIM-DAS into existing BIM software will provide a basis for the comparison of deconstructability of building models during design.

Keywords: *Building Information Modelling; Building deconstruction; Design for Deconstruction; Demolition Waste Minimisation; Design performance assessment; Scoring Scheme.*

1 Introduction

The increasing global urbanisation has resulted in high volume of Construction, Demolition and Excavation Waste (CDEW) from which demolition waste contributes up to 31.8 million metric tonnes yearly in the UK alone (WRAP 2009). With so many demolitions taking place annually, its environmental and economic impacts cannot be ignored because building materials become unrecoverable and eventually sent to landfills. Tackling this problem calls for a strategic approach to planning for recovery of building materials and components for reuse or recycling. This requires dealing with the problem at source, which is usually at the design stage by designing for deconstruction (DfD) to avoid demolition after the end of life of buildings. Although literature abounds on causes and management of CDEW, only few studies have been conducted to mitigate the generation of end of life waste right from the early design stages. Even most of these few studies focus on disposal cost estimation (Chen et al. 2006; Cheng and Ma 2011; Yuan et al. 2011) and waste quantification during demolition (Cochran et al. 2007; Rosmani and Hassan 2012; Wu et al. 2014). Considering the fact that end-of-life activities generate the largest volume of waste (DEFRA 2012), there is need to plan for the end of buildings right from the design stages.

Evidence shows that up to 50% of CDEW could be diverted from landfill through a well-planned deconstruction strategy (Kibert 2008). This shows that in the UK alone, about 16 million tonnes of waste could be diverted from landfills (DEFRA 2011), while saving over £1.3 billion in terms of landfill tax and waste transportation. Despite these opportunities accruable from deconstruction, research efforts on design performance assessment have been concentrated on buildability and construction waste assessment. Examples of such systems include Building Design Appraisal System – BDAS (CIDB 1995a), Building Waste Assessment Score – BWAS (Ekanayake and Ofori 2004), and Construction Quality Assessment System – CONQUAS (CIDB 1995b). These performance assessment tools are concerned with the impact of design on construction stage but not with the end of life of buildings.

Blengini & Carlo (2010) highlighted that it is difficult to carry out life cycle analysis towards the end of life stage during design stage because information is still scanty. However, construction sustainability could be achieved if considerable effort is put in design with future benefits in mind (Ajayi *et al.*, 2015). In this way, Design for Deconstruction (DfD) will increase the cost-effectiveness of material recovery and reuse from the early design stages (Davison and Tingley 2011). Despite the general knowledge that design could initiate effective building deconstruction (Crowther 2005; Guy et al. 2006) and the attempts to quantify the benefits of DfD, no practicable design tool has been provided to substantiate these claims. Existing design tools for deconstruction have been design guides, such as ICE deconstruction protocol, that provide no quantifiable measure similar to BDAS, BWAS, and CONQUAS. Other tools such as building end of life analysis tool (Dorsthorst and Kowalczyk 2002), NetWaste tool (WRAP 2011b), Design out waste for buildings tool (WRAP 2011a), and Sakura (Tingley 2012) focus more on material analysis for investigating end of life impact of buildings.

Apart from the above limitations, increasing adoption of Building Information Modelling (BIM) within Architecture, Engineering and Construction (AEC) industry (Arayici et al. 2011) requires a holistic rethink of entire construction activities. This means that any promising innovation within the AEC industry requires BIM compliance (Ajayi *et al.*, 2015). Laying on this premise, the overall aim of this paper is to detail the development of BIM based Deconstructability Assessment System (BIM-DAS) to provide an objective and measurable system for building deconstructability during the design stage. This scoring system forms a basis for comparative analysis building models to choose the option with the least end of life impact on the environment. Accordingly, the specific objectives are:

i) To identify critical design principles that ensures building deconstructability.
ii) To develop an objective system, i.e. BIM-DAS, for scoring the degree of building deconstructability.
iii) To test the performance and usability of BIM-DAS.

While adopting a positivist theoretical framework, this study uses experimental research and case study as research methodology to achieve its objectives. As such, an in-depth review of literature was carried out to identify key features that could be used for assessing the performance of DfD. Thereafter, the key features were used to develop BIM-DAS using mathematical modelling approach, which is based on efficient material requirement planning. At the end, BIM-DAS was tested using case study design.

The research paper starts with a discussion of the concept of design for deconstruction, key design principles influencing deconstruction, and the role of BIM in achieving effectual deconstruction. After this, a full discussion of the research methodology preceded discussion of how BIM-DAS was developed. A discussion on the evaluation of BIM-DAS through a case study design is then presented before culminating the paper ends with a conclusion and areas of further research.

2 Design for Deconstruction as a Means to an End

Deconstruction is "*the whole or partial disassembly of buildings to facilitate component reuse and material recycling*" (Kibert, 2008) to eliminate demolition through the recovery of reusable materials (Gorgolewski 2006). This is with the aim of rapid relocation of building, reduced demolition waste, improved flexibility and retrofitting, etc. (Addis 2008). Despite a growing discrepancy of opinion on whether CDEW could be completely eradicated (cf. Yuan & Shen, 2011; Zaman & Lehmann, 2013), existing studies shows that effective deconstruction could drive construction waste eradication initiatives (Guy et al. 2006; Densley Tingley and Davison 2012; Akbarnezhad et al. 2014). Example of such initiative is the EU target of zero waste to landfill by 2020 (Phillips et al. 2011). Apart from helping to divert waste from landfills, deconstruction also enables other benefits, which include: (a) *environmental benefits*: by reducing site disturbance (Lassandro 2003), harmful emission, health hazard (Chini and Acquaye 2001) and preserving the embodied energy (Thormark 2001) through material reuse; (b) *social and economic benefits*: by providing business opportunities through material recovery, reuse and recycling; and providing employment to support deconstruction infrastructure.

To enable a well-planned deconstruction, conscious efforts must be taken by architects and engineers right from the design stages. (Kibert 2008). As such, the eventual purpose of deconstruction must be identified to guarantee the success of DfD. This will enhance the understanding of relevant design strategies and tools required for deconstruction. This section therefore contains a review of extant literature on types of deconstruction, DfD techniques, theory of building layers and BIM as a tool for DfD.

2.1 Types of Deconstruction

Two activities are possible at the end of life of buildings, which include demolition and deconstruction as shown in Figure 1. Demolition as a building removal strategy is primarily aimed at disposal to landfill with little consideration for material recovery. On the other hand, deconstruction is carried out to recover toxic materials from buildings for safe disposal or to divert waste from landfills through material recovery. For example, harmful substances such as asbestos needs to be safely removed through careful deconstruction from old buildings to avoid occupational exposure (Frost et al. 2008). According to Crowther (2005), deconstruction of buildings without toxic materials could be for four main purposes, which include (i) relocation of buildings, (ii) component reuse in other buildings, (iii) material reprocessing and (iv) material recycling. This is inline with the viewpoint of Kibert (2003) who suggests that realisation of effective DfD for multiple purposes will significantly reduce CDEW and helps to divert waste from landfills.

Deconstruction for building relocation involves the recovery of all the building materials and components without generation of waste. This is only possible if all the building materials and components are separable and reusable (Crowther 2005). Although it is impractical to achieve 100% material recovery, McDonough & Braungart (2002) argued that recovery of building components for relocation and reuse remains the most preferred deconstruction purpose because it requires the least energy and new resources (Oyedele *et al.*, 2014). This is because other purposes of deconstruction require additional energy and materials to reprocess or recycle recovered materials (Jaillon and Poon 2014). The term DfD used in this study therefore encapsulates design for the purpose of recovery for building relocation and component reuse.

This takes a cue from the fact that it is becoming a common practice to recycle an entire building and that a more significant challenge is designing a building that could be deconstructed for component reuse with minimal reprocessing. This task therefore necessitates the requirement to understand the complexity of intertwined processes of building design practice, DfD techniques and associated factors. As such, next section takes a holistic approach in discussing existing perspectives on DfD principles and how interplay among them could ensure successful building deconstruction.

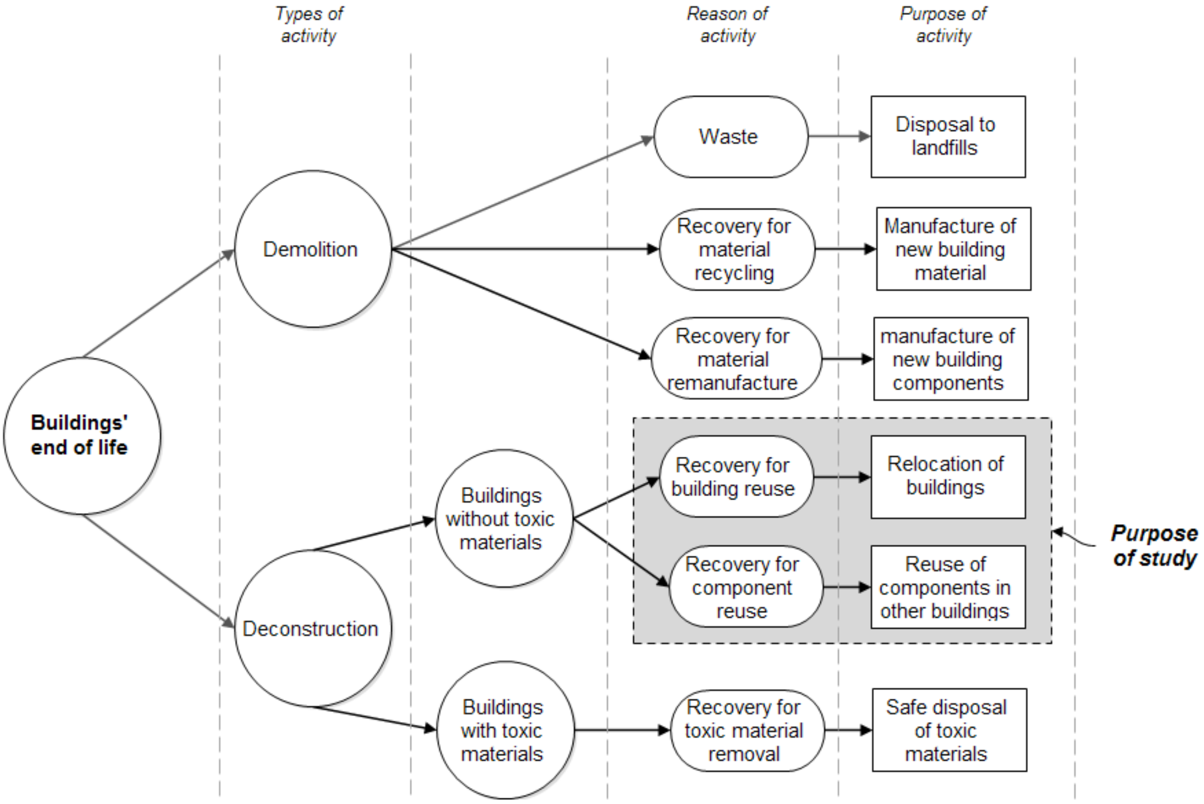


Figure 1: Types and purpose of buildings' end of life

2.2 Design for Deconstruction Techniques

According to Warszawski (1999), there are various design rules that should be followed in order to enhance deconstructability of buildings. These rules help to maximise the flexibility of designs, thereby enhancing building re-modification and disassembly. Guy *et al.* (2006)

argues that designing for deconstruction requires an in-depth conceptual and theoretical exploration of the make-up of building systems using both holistic and systemic approach. This is to capture the complexity and multiplicity of the makeup of buildings as well as interactions among building elements. This idea underscores the theory of building layers where parts of buildings are organised into subsystems known as layers. The layers structure building elements according to their life expectancy (Habraken and Teicher 2000). Accordingly, Brand (1994) highlighted six building layer which are site, structure, skin, services, space plan and stuff as shown in Figure 2.

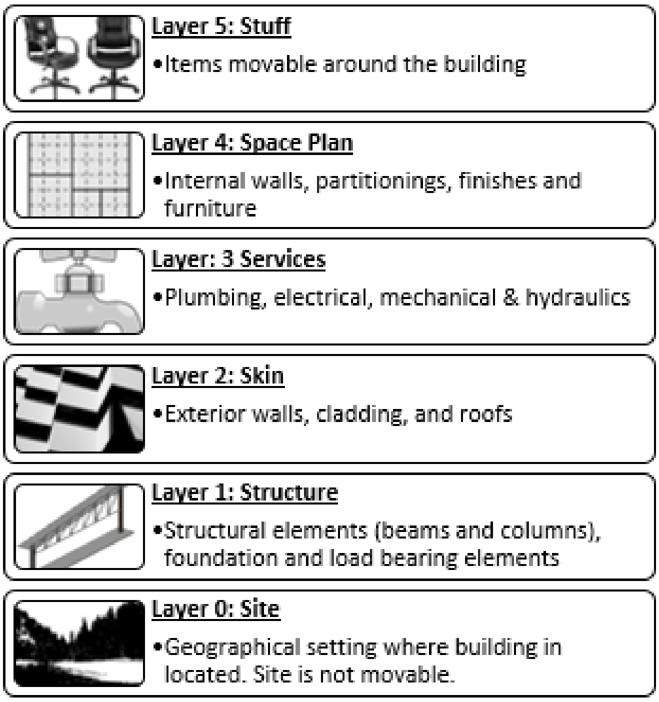


Figure 2: Building layers. Adapted from Brand (1994).

The theory of building layer is important to keep building subsystems as independent as possible so that components on higher layers could be altered or replaced without affecting lower layers. According to Habraken (2000), building layers makes DfD technically possible because layers' interfaces become points of deconstruction. This has led researchers to produce design principles needed for ensuring end of life deconstruction. For example, Guy *et al.* (2006) and Crowther (2005) produced a comprehensive list of general design concepts and principles for deconstruction. These research works provide a solid foundation for contemporary DfD process and are majorly driven by efficient building elements selection to facilitate easy disassembly (Addis 2008).

The highlight of building elements selection process include: (i) the specification of durable materials (Tingley 2012); (ii) using materials with no secondary finishes (Guy and Ciarimboli 2008); (iii) using bolt/nuts joints instead of gluing (Chini and Balachandran 2002; Webster and Costello 2005); (iv) avoiding toxic materials (Guy et al. 2006); and (v) using prefabricated assemblies (Jaillon et al. 2009). In addition to these, Guy *et al.* (2006) 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 (Hobbs and Hurley 2001; Crowther 2005) 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). These requirements place huge responsibilities on architects and engineers at ensuring that design has the least impact on the ecosystem throughout the building's lifecycle (Yeang, 1995). Though selecting appropriate building elements that facilitate deconstruction may increase the project cost, architects and engineers must ensure that the cost of DfD does not exceed the cost of recoverable materials minus the actual cost of disposal (Billatos and Basaly 1997), i.e.:

$$(Cost\ of\ DfD) < (Value\ of\ Recovered\ Materials) - (Cost\ of\ Disposal) \tag{1}$$

Meanwhile, DfD principles go beyond building element selection (Crowther 2005) since other studies have shown that material handling (Couto and Couto 2010), building design methodology (Latham 1994), and design documentation (Andi and Minato 2003) are all part of DfD principles. This study however is limited to key DfD principles required in building elements selection as presented in Table 1.

Focusing on the studies presented in Table 1, through which the consciousness of deconstruction is stimulated during material specification, opens up a genuine foundational requirement for DfD. Nevertheless, these studies have their challenges. First, the set of studies only offers a conceptual framework by providing factors that must be considered during design (Tingley 2012). As such, the studies fail to provide a methodological framework needed to understand how to implement the design principles. Another challenge is that none of the studies provides an objective measure of performance for the principles. These limitations therefore reveal the need to take a holistic approach to investigating the DfD principles empirically and develop a framework for integrating DfD performance measure into BIM.

Table 1: Material Selection Design for Deconstruction Principles

No	**Design Principle**	**Reference**
1.	Use reusable materials	(Webster and Costello 2005; Guy et al. 2006)
2.	Use nut/bolt joints instead of nails and gluing	(Crowther 2005; Webster and Costello 2005; Guy et al. 2006)
3.	Use prefabricated assemblies	(Crowther 2005; Guy and Ciarimboli 2008)
4.	Avoid composite materials during design specification	(Crowther 2005; Webster and Costello 2005; Guy et al. 2006; Guy and Ciarimboli 2008)
5.	Minimise number of building components	(Crowther 2005; Webster and Costello 2005; Guy and Ciarimboli 2008)
6.	Minimise types of building components	(Chini and Balachandran 2002; Crowther 2005; Webster and Costello 2005; Guy et al. 2006; Guy and Ciarimboli 2008)
7.	Avoid toxic and hazardous materials	(Crowther 2005; Guy et al. 2006)
8.	Use of recyclable materials	(Chini and Bruening 2003; Crowther 2005; Guy et al. 2006)
9.	Avoid materials with secondary finishes	(Crowther 2005; Guy and Ciarimboli 2008)

2.3 Roles of BIM in Design for Deconstruction

BIM, as Integrated Product Delivery (IPD) approach, enables effective communication and collaboration among stakeholders. This facilitates transparent access to shared information, controlled coordination and monitoring of construction processes (Grilo and Jardim-Goncalves 2010). These capabilities encourage the involvement of all stakeholders’ right from the conception of the building project through the entire lifecycle (Eastman et al. 2011) and allow partners across various disciplines to collaborate effectively on building projects. According to Eadie *et al.* (2013), a distinguishing feature that makes BIM applicable to all work stages is the accumulation of building lifecycle information. As such, information on building requirements, planning, design, construction and operations related information can be accumulated and accessed at the end of life of buildings.

Another functionality of BIM that aids its wide acceptability is the ability to simulate building performances such as cost estimation, energy consumption, lighting analysis, etc. According to Eastman *et al.* (2011), building performance analysis provides a platform for functional evaluation of building models before the commencement of construction. This allows comparison of design options to identify potential design errors and to select the most cost-effective and sustainable solution. Despite the benefits of building performance analysis and the environmental/economic impacts of end of life waste, none of the existing BIM software has capabilities for end of life waste performance analysis. This gap calls for a rethink of BIM functionalities towards capacity for end of life waste analysis and simulation right from early design stages. This will help to capture and address end of life concerns at a stage where design changes are cheaper.

3 Research Methodology

After a review of extant literature, it became clear that a methodology that drives objectivity is needed for developing a framework to realise BIM-DAS. This reveals the need for systemic operationalisation of practices in driving genuine understanding of actions (Gray 2009). According to Creswell (2014), a study that requires such degree of objectivity in driving an acceptable consensus necessitates a positivist worldview. This therefore positions the study within an objectivist epistemology where a single “real reality” exists (Crotty 1998). This perspective helps to operationalise concepts into measurable entities (Guba and Lincoln 1994). In line with positivism, the paper adopts review of literature, mathematical modelling and case study design as research methods. After a thorough review of extant literature, key principles for DfD were identified and developed into a framework. This framework was then used to develop BIM-DAS using mathematical modelling techniques. After this, BIM-DAS was tested using case study approach to demonstrate its capabilities and to evaluate its overall performance.

In deciding the degree of deconstructability of design, architects and engineers must adopt an automated, but objective, approach with general acceptability. To accomplish this, design principles for deconstruction must be conceptualised, mathematically captured and developed into a model. This will reduce effort and time required for analysis as well as eliminating human errors. As such, the BIM-DAS model development follows the processes of problem description, formulation of a mathematical modelling, obtaining mathematical solutions to model, simulation with the model and interpretation of the results. This approach helps to characterise building materials and their properties such that given a BIM design, the mathematical model could assess its DfD performance by assigning a BIM-DAS score to the design. To evaluate BIM-DAS, this study adopts a case study approach using a comparative analysis of design typologies to evaluate the performance of BIM-DAS. As such, three case studies of a two-storey residential building located in the UK were developed with a ground floor area of 492 m^2. The floor plan of the case study is shown in Figure 3 and the design characteristics are presented in Table 2. While it is generally believed that residential buildings have long serviceable life, houses built to be deconstructed are becoming more popular to aid future metropolitan planning and relocation (Kibert, 2008). Examples of deconstructable residential buildings include block of flats and condominiums in city centres (Budge, 2013).

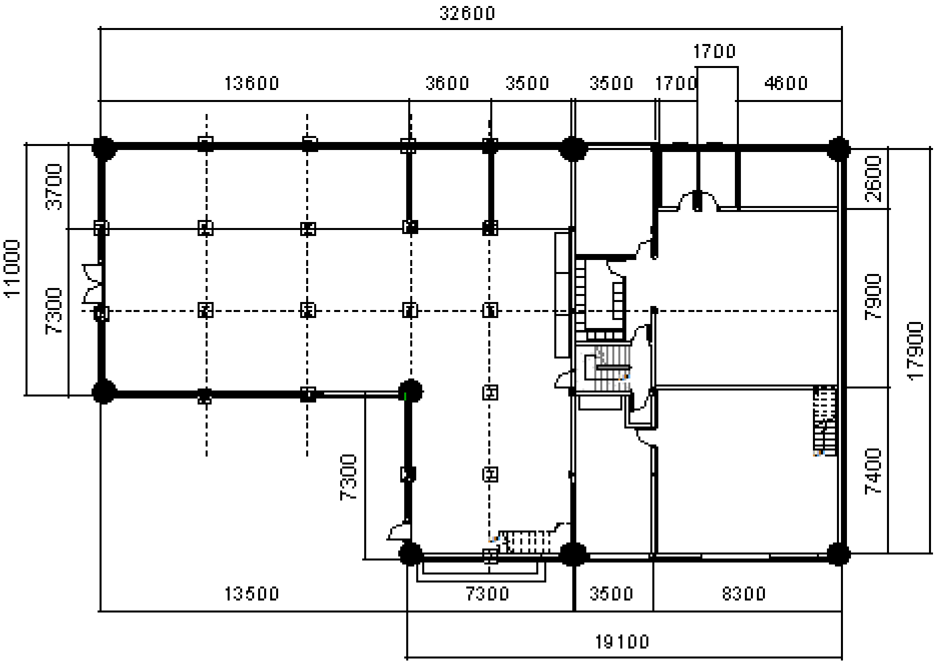


Figure 3: Floor Plan of Case Study (Source: Author)

Table 2: Design Characteristics of Case Study

Building type: Residential
Number of floors: 3
Ground floor area: 492m^2
First floor ground floor area: 351m^2
Second floor ground floor area: 351m^2
Floor to ceiling height: 2.8m
Second floor roof area: 402m^2
Low level roof: 168m^2

Using the design characteristics shown in Table 2, three case studies were designed with three different major material types, i.e., steel, timber and concrete. This approach was used to assess and compare the building deconstructability score of the three building types. The aim of the comparative evaluation is to ascertain which of the building types has greater deconstructability potential.

4 BIM-DAS Model Development

This section presents the general characteristics of the mathematical model developed for assessing the performance of DfD. The variables used in the development of the model are presented in Table 3. Although building parametric models are composed of n-D spatial distribution of materials and components, however, the focus of the model development is to employ elemental breakdown of material take-off. First, a formal definition of design model for deconstruction based on material specification is presented. This helps to identify independent variables contributing to BIM-DAS. Second, deconstruction related variables are incorporated in BIM design models using Revit software. Lastly, BIM-DAS was developed and evaluated.

Table 3: Notations and Descriptions of Variables

Notation	Description
M	Set of materials, i.e., $M = \{M_1, M_2, \dots, M_n\}$
C	Set of components, i.e., $C = \{C_1, C_2, \dots, C_n\}$
E	Set of connector, i.e., $E = \{E_1, E_2, \dots, E_n\}$
r_1	Is *true* if specimen is reusable
r_2	Is *true* if specimen is recyclable
P	Is true if specimen is prefabricated
c	Connection type; $c = \{c_f, c_b, c_n, c_d\}$*
n	Total number of specimen
t	Material type of specimen; t = {steel, concrete, timber, etc,}
x	Is *true* if specimen is toxic
s	Is true if material has secondary finishes
v	Volume of specimen (mm^3)
φ	Spatial position and orientation of specimen
p	Position of specimen in 3D space
r	Rotation of specimen in 3D space

* c_f = Fixed connection, c_b = bolted connection, c_n = nailed connection and c_b = dowel connection

4.1 Design Model for Deconstruction (DMD)

Given a 3D building model with a well-defined bill of quantity of materials (*M*), components (*C*) and connectors (*E*), then a Design Model for Deconstruction (*DMD*) can be formally defined as three (3) tuple:

$$DMD =< M, C, E > \tag{2}$$

This definition is restricted to the four main assumptions:

1) All specimen, i.e., $S = (M \cup C \cup E)$ are represented within the building model using a spatial function φ that determines the position p and rotation r of such specimen, i.e.,
$$M \cup C \cup E = \{S \mid S \in M \ or \ S \in C \ or \ S \in E\} \tag{3}$$
$$\varphi : S \epsilon (M \cup C \cup E) \times (p, r) \tag{4}$$
2) A set of specimen S cannot be empty, i.e: $S \neq \emptyset$
3) A set of specimen S must be composed of tangible object and properties of all specimen $S_i \ \epsilon \ S$ must be identifiable:
$$\forall_{S_i \in S} \ [tangible(S_i)] \tag{5}$$
4) The boundary of all specimen $S_i \ \epsilon \ (M \cup C \cup E)$ must not empty, i.e., a specimen S_i cannot be self-interacting. As such, S_i must be connected to one or more specimen $S_j \in S$.

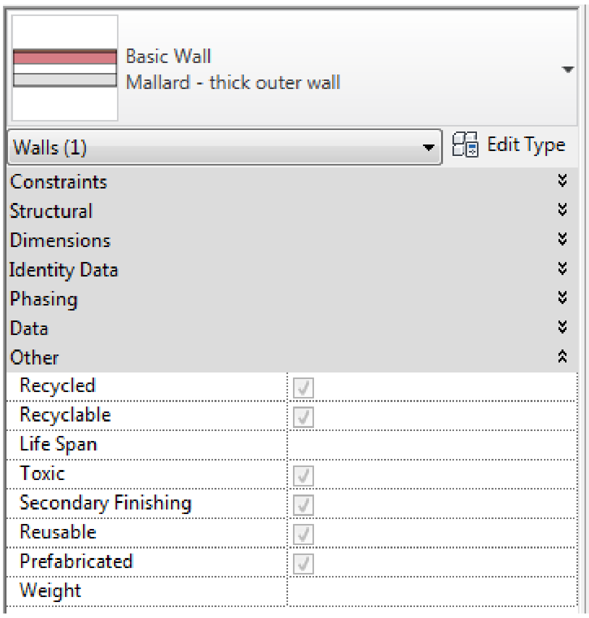
Based on these assumptions and the set of variables defined in Table 3, we can define the properties of a specimen S_i using an eight (8) tuple:

$$S_i =< r_1, r_2, c, P, n, t, x, s > \tag{6}$$

Equation (6) identifies specimen S_i as an object with a fixed set of properties that uniquely describes S_i. To facilitate easy access of relevant properties of specimen S_i, the study adopts an object-oriented notation. For example, the connection type of S_i could be assessed using the notation $S_i.c$ and the type of S_i will be $S_i.t$. Having provided the formal definition of a design model for deconstruction and described the properties of each element, a BIM based approach was used to incorporate all the deconstruction related parameters into the building model. This is to enable the automated computation of DDAS. The process for achieving this is detailed in the following section.

4.2 BIM-based Deconstructability Assessment System

An important factor that makes BIM relevant in building design is its ability to capture object parameters automatically for simulating building performances. To leverage upon this, current BIM parametric modelling software allows user-specific object parameters to extend built-in parameters. Accordingly, custom parameters were created to capture various aspects of building deconstructability. This includes recyclability attributes, reusability attributes, expected life of specimen, toxicity of specimen, assemblage attribute, finishing on specimen and Joint/connector attributes. Figure 4 shows a specimen property tab showing the custom parameters.



Recycled	☑
Recyclable	☑
Life Span	
Toxic	☑
Secondary Finishing	☑
Reusable	☑
Prefabricated	☑
Weight	

Figure 4: Custom Parameters in Revit

During a deconstruction process, the total End of life waste (E_w), which is the amount of building elements (measured in tonnes) that cannot be recovered, could be computed as:

$$E_w(\text{tonnes}) = B_q - T_r + \varepsilon \tag{7}$$

Where B_q is the bill of quantity (tonnes), T_r (tonnes) is the total recoverable items from B_q and ε is the residual. ε is included in Equation (7) to capture waste due to transportation, human errors and natural disaster. The use of weight metrics here is because materials used on projects and CDEW from project site are quantified in weights. The use of weight of elements may be biased towards heavyweight elements whereas deconstruction is more concerned with the recovery of high-embodied impact elements. However, since the associated embodied energy (MJ) of an element is directly proportional to its mass (kg), the recoverable end of life energy could be computed as a product of the embodied energy (MJ/kg) and mass. Therefore, the lost energy (E_E) at the end of life could be calculated from Equation (7) as:

$$E_E(\text{MJ}) = E_C - E_D + \varepsilon \tag{8}$$

Where E_C is the total embodied energy and energy needed for building construction, E_D is the total embodied energy plus the energy needed for building deconstruction. ε remains the residual. The aim of an effective deconstruction activity, especially for building relocation, is to make $E_w + \varepsilon = 0$ and $E_E + \varepsilon = 0$ i.e. zero waste generation and zero energy loss. To incline this study towards a metric that AEC practitioners can easily relate to and to simplify the process of model development, Equation (7) becomes:

$$T_r = B_q \tag{9}$$

Equation (9) shows an ideal situation of a fully reusable building where all elements with environmental burden are recovered. In realising a DAS score, the higher the score the higher the total recoverable items with high-embodied impact, i.e.:

$$T_r \; \alpha \; DAS \tag{10}$$

Since B_q is constant, T_r must be maximised towards the value of B_q in order to minimise E_w. Therefore, setting the maximum DAS score at 1.0, which reflects the highest level of building deconstructability, will make Equation (10) to become:

$$\frac{T_r}{B_q} = DAS = 1.0 \tag{11}$$

Equation (11) shows that DDAS is a percentage of total recoverable material (T_r) to the total quantity of material used in building. Therefore, T_r could be calculated as:

$$T_r = B_q \times DDAS \tag{12}$$

Meanwhile, it is impractical to calculate DAS score for individual constituent of a building structure because building elements are matrix of interacting objects. As such, DAS score will be calculated for the entire building. This is done using a sum of Deconstructability score (D_{score}) and Recovery score (R_{score}) as shown in Figure 5. D_{score} determines the extent to which a building could be disassembled for reuse or relocation while R_{Score} represents the ease of material recovery and reuse after end of life of the building. Although there are certain issues that bothers on the concept of materials reuse and recyclability. In particular, the area of residual performance, recertification, and legal warranties of recovered building elements after several years of usage (Kibert *et al.*, 2001). For example, evidence shows that recovered elements such as wood cannot be regraded and can only be used for low market applications and non-structural use (Falk, 2002). With this in mind, this study is based on the presupposition that the reusability and recyclability of building elements could be determined during design and that the value of building items is retained at the end of life. As impractical as this may be, it provides a grip on achieving the objectives of the current study.

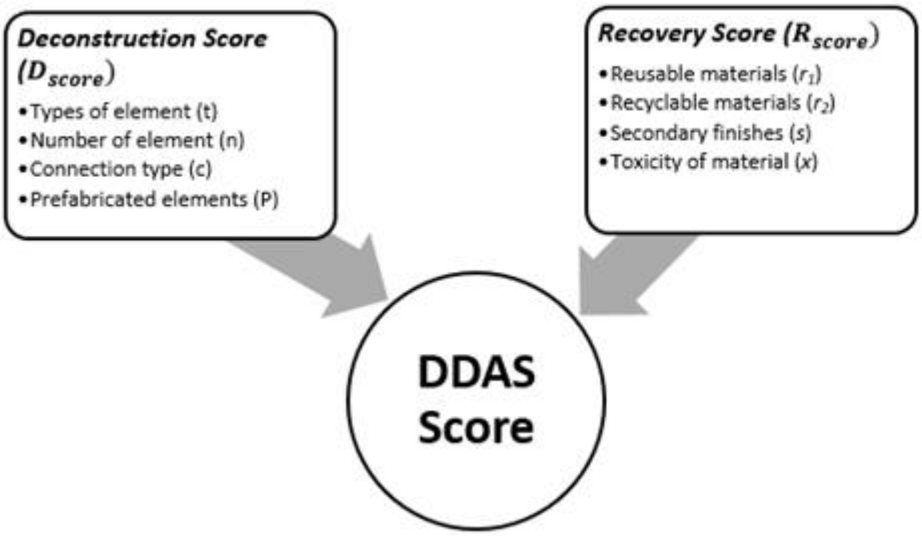


Figure 5: Parameters for Calculating DAS for Subsystem

Separating DAS score into D_{score} and R_{score} is because Crowther (2005) highlighted that not all principles that guarantees material reusability or recyclability contribute towards building deconstructability. In the same way, there are principles that encourages deconstructability but do not guarantee that the material recovered will be useful. For example, specifying materials without secondary materials enables reusability but does not contribute to building deconstructability. Using this approach, the DAS score could be computed as a weighted sum of D_{score} and R_{score}, i.e.:

$$DAS = \alpha D_{score} + \beta R_{score} \tag{13}$$

The maximum value for D_{score} and R_{score} is also set at 1.0. Parameters $\alpha\ and\ \beta$ are the weighting function that determines the level of significance of the constituents of *DAS*. In this study, the same level of significance of 0.5 was assumed for the individual scores, i.e.:

$$DAS = 0.5D_{score} + 0.5R_{score} \tag{14}$$

Although, assuming the same weight for the two factors may be impractical as D_{score} and R_{score} may have varying level of significance, yet this assumption provides a reference point for computing *DAS* score. Based on the assertion that every object in a building model can be uniquely identified and described, the constituents of *DAS* score for subsystems can be computed as follows:

$$D_{score} = \frac{\mathrm{t}_n + d_c + R_P}{3} \tag{15}$$

$$R_{score} = \frac{R_1 + R_2 + R_{\bar{s}} + R_{\bar{x}}}{4} \tag{16}$$

Where:

t_n is the material type–number ratio for subsystem and it is calculated as:

$$t_n = 1.0 - \left(\frac{t}{n}\right) \tag{17}$$

d_c is the ratio of demountable connections, i.e.,

$$d_c = \frac{C_b + C_d}{C_b + C_d + C_n + C_f} \tag{18}$$

R_P is ratio of prefabricated elements, R_1 is ratio of reusable elements, R_2 is the ratio of recyclable elements, $R_{\bar{s}}$ is ratio elements without secondary finishing and $R_{\bar{x}}$ is ratio of non-toxic elements.

Equation (14) thus becomes:

$$DAS = 0.5\,\frac{\mathrm{t}_n + d_c + R_P}{3} + 0.5\,\frac{R_1 + R_2 + R_{\bar{s}} + \overline{R_{\bar{x}}}}{4} \tag{19}$$

The mathematical model shown in Equation (19) represents the final equation for calculating *DAS*. This model will thus be used to assess the performance of DfD using case studies.

5 Model Evaluation and Results

This section presents the results of the evaluation of *DAS* using a hypothetical case study approach. This was achieved using three case studies of a building model with different material specifications. The case studies include a steel structure, a timber structure and a concrete structure. The building models were developed in Revit and the inventory of materials is as shown in Table 4. Accordingly, a bill of quantity schedule for each model was estimated to determine the details of the constituents of the buildings. This was exported into a Microsoft Excel sheet to aggregate the building constituents for the initial analysis. *DAS* score for each design typology was then calculated using the mathematical model developed.

At this point, it is important to show how values of parameters needed for the calculation of *DAS* score will be derived. This was done using a lookup table of possible materials types for building subsystems as shown in Table 5. Accordingly, *DAS* score of each building was calculated based on the design specifications to achieve the objectives of the study. Table 6 shows the values of the parameters and *DAS* score for the three case studies. From this result, the steel structure building has the highest *DAS* score of 0.935 due to very high demountable connections and prefabricated components. In addition, the steel structure has minimal materials with secondary finishing, thus contributing to the high R_{score}. Although the timber structure has no demountable connection and lower prefabricated elements, it has a higher *DAS* score than the concrete structure. This is primarily because the timber structure has higher recyclable and reusable potentials than concrete structures.

Table 4: Inventory of materials for design options

Item	Specific characteristics
Structural frame system	A. Prefabricated steel with bolted connections
	B. Hardwood timber post with nailed connections
	C. Concrete with bolted connections
Foundation system	A. H-pile foundation
	B&C. Concrete ground beam
Wall system	A. Curtain walls with bolted connections
	B. Cladded timber cavity walls filled with nailed connections
	C. Concrete wall with paint finishing
Floor system	A. Gypframe steel flooring with carpet
	B. Timber board with I-section timber frames with ceramic tiles
	C. Concrete floor with carpet
Ceiling system	A. Aluminium strips on prefabricated steel frame
	B. Pressured-treated timber planks on timber frames free of copper chromium acetate
	C. Soffit plaster and paint finishing
Roof system floor	A. Insulated steel plate flat roof on steel truss
	B. Insulated slate roofing sheet on timber truss
	C. Concrete roof with sand and cement screed
Window and doors	A. Steel windows and doors with steel frame
	B. Timber windows and doors with timber frame
	C. Double-glazed glass with aluminium frame

Note: **A.** is a steel structure; **B.** is a timber structure; and **C.** is a concrete structure.

To understand the resultant effect of individual factors on D_{score}, R_{score} and DAS, factor selection process was carried out. This was done by omitting certain factors in the model to see how the results are affected. This will help to identify key factors contributing to the calculation of D_{score}, R_{score} and DAS. To achieve this, Mean Squared Error (MSE) between the actual and the new values were calculated using Equation (20). Where DAS is the actual value and $\widehat{DAS}$ is the calculated value.

$$MSE = \sum_{i=1}^{n}(\widehat{DAS} - DAS)^2 \tag{20}$$

Table 5: Material options for building system

Systems and options	**Recyclable (r_1)**	**Reusable (r_2)**	**Toxic (x)**	**Sec. Finish (s)**	**Connection type**
1. Structural frame system					
Steel with fixed connections	✓	✓	×	×	c_f
Steel with bolted connections	✓	✓	×	×	c_b
Timber with steel dowels connections	✓	✓	×	×	c_d
Timber with bolted connections	✓	✓	×	×	c_b
Timber with nailed connections	✓	✓	×	×	c_n
Concrete with fixed connections	✓	×	×	✓	c_f
Concrete with bolted connections	✓	✓	×	✓	c_b
2. Structural Foundations					
H-Pile foundation	✓	✓	×	×	c_b
Concrete ground beam	✓	×	×	×	c_f
3. Wall system					
Demountable dry internal wall	✓	✓	×	✓	c_b
Curtain wall	✓	✓	×	×	c_b
Brick/block cavity wall	✓	×	×	✓	c_b
Cladded timber cavity wall	✓	×	×	✓	c_n
Steel framed wall	✓	✓	×	×	c_b
Concrete wall with paint finish	✓	×	×	✓	c_f
4. Floor system					
Concrete floor with ceramic tiles	✓	×	×	×	c_f
Concrete floor with carpet	✓	×	×	×	c_f
Timber floor with carpet	✓	✓	×	×	c_n
Timber floor with ceramic tiles	✓	✓	×	×	c_n
5. Ceiling system					
Gypsum ceiling with steel frame	✓	×	×	✓	c_f
Aluminium strips with steel frame	✓	✓	×	×	c_f
Soffit plaster and paint	×	×	×	✓	c_f
Timber planks with timber frame	✓	✓	×	✓	c_n
Ceiling tiles with metal frame	✓	✓	×	×	c_f
6. Roof system					
Tiled roof on timber beam	✓	✓	×	×	c_n
Metal panel on steel truss	✓	✓	×	×	c_b
Metal panel on timber truss	✓	✓	×	×	c_f
Slate roofing sheet on timber truss	✓	✓	×	×	c_n
Concrete roof with sand/cement screed	✓	×	×	✓	c_f
7. Doors and windows					
Glass with aluminium frame	✓	✓	×	×	c_f
Timber with timber frame	✓	✓	×	✓	c_n
Steel with steel frame	✓	✓	×	×	c_b

Table 6: *DAS* score for Case Studies

Case Study	t	n	t_n	d_c	R_p	r_1	r_2	x	s	**D_{score}**	**R_{score}**	**DAS**
A	25	256	0.90	0.71	1.00	1.00	1.00	1.0	1.00	0.87	1.00	0.935
B	20	256	0.92	0.00	0.28	1.00	0.71	1.0	0.57	0.40	0.82	0.610
C	23	256	0.91	0.14	0.42	0.85	0.28	1.0	0.43	0.49	0.64	0.565

The result of the factor selection shows that ratio prefabricated elements (R_p) and ratio of demountable (d_c) have the highest significance as shown in Figure 6 since removing 'R_p' and 'd_c' results in a high MSE value of 0.13353 and 0.1145 respectively. This thus shows that removing 'R_p' and 'd_c' from the model will considerably affect the value of *DAS*. After this, a simple logistic regression analysis was carried out to obtain an equation such that $DAS = f(R_p\ , d_c)$. This yield a mathematical representation of statistical correlation between DAS and ratio of prefabricated element and ratio of demountable connections given as:

$$DAS = 0.43 + (0.605 \times R_p\ ) + (0.18 \times d_c) \qquad (21)$$

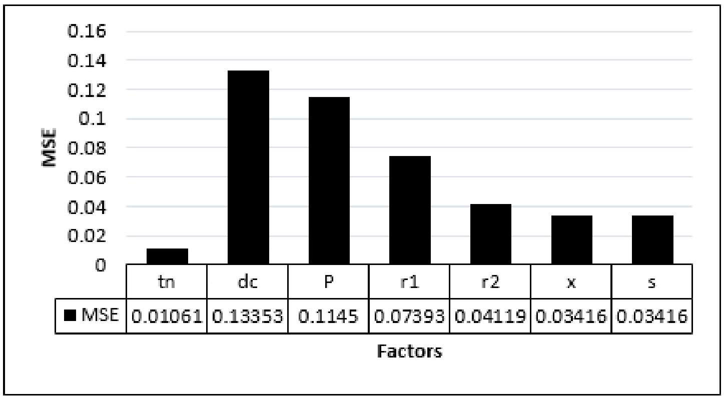


Figure 6: Mean squared error from factor analysis

To verify the accuracy of this model, Equation (20) was validated against the initial case study and the result is presented in Table 7. The nature of the residuals shows that the model performs well in predicting the value of *DAS* since the residual is negligible in all cases. The nature of the residuals shows that it is possible to predict DAS with minimal error using two parameters instead of the initial set of nine parameters. This result clearly demonstrates that there exists a strong linear and positive relationship among the *DAS* predicted by the model, '*P*' and 'd_c'.

Table 7: Model Validation

Case Study	**d_c**	R_p	**DAS**	**Predicted DAS**	**Residuals**
A	0.71	1.00	0.935	0.935	1.11e-16
B	0.00	0.28	0.610	0.610	0
C	0.14	0.42	0.565	0.565	0

6 Discussion

Using the approach discussed in this paper, BIM-DAS score of design models could be calculated to assist designers in making appropriate decisions and compare alternative designs. This is towards the delivery of the most sustainable design in terms of building deconstruction. Accordingly, the study shows that the use of prefabricated assemblies and demountable connections are essential factors that ensure building deconstructability. These two factors signify several implications for the AEC industry in addition to confirming best practices. First, the use of prefabricated assemblies helps to reduce on-site waste and material use. Evidence shows that 84.7% of on-site construction waste could be avoided by adopting prefabrication. In addition, Jaillon and Poon (2014) highlight other benefits of prefabrication in ensuring design for deconstruction. These include improved quality control, improved on-site environment, improved health and safety, and improved ease of construction. Although it is true that the use of prefabrication is limited by the initial high cost (Hsieh 1997), however, it must also be recognised that the benefits outweighs the cost (Baldwin *et al.*, 2008). Several studies (Baldwin *et al.*, 2008; Tam *et al.* 2005; Lu & Yuan 2013) have shown that the use of prefabricated elements, such as prefabricated concrete, reduces CDEW. According to Jaillon *et al.* (2009), the use of precast construction could result in 52% reduction in CDEW.

Second, the use of demountable connections ensures deconstruction by allowing building subsystems to be easily disconnected from each other without damage. Based on this, the use of mechanical joints (such as bolts and nuts and dowels) should be encouraged instead of chemical joints (adhesives) and fixed joints (welding and riveting) (Crowther 2005). Using mechanical joints allows the recovery of building elements in prime conditions for reuse. Akbarnezhad *et al.* (2014) highlighted that using mechanical connections engenders environmental sustainability through waste minimisation, resource usage reduction and embodied energy preservation. Embodied energy is preserved because demountable connections allow material reuse rather than recycling or remanufacture. Accordingly, demountable connections should be encouraged in building elements such as structural frames and beams, curtain walls, internal walls, ceilings, roofs etc.

While Gorgolewski (2006) claims that bolted connections are easily achievable in steel structures, it is also possible in other structures such as timber and concrete. In steel structures, the use of demountable H-pile foundation, bolted structural frames and beams, and bolted curtain walls should be particularly promoted to enable prefabrication and easier deconstruction. In the case of timber structures, not only the use of prefabricated assemblies and demountable connections must be considered, but also the durability of the wood. This is to enable the reusability of timber components because wood has more value in reuse than in recycling. On the other hand, evidence shows that reinforced concrete structures are not suitable for deconstruction because the structures are difficult to take apart without any damage (Tingley 2012). This makes reuse of concrete structures generally difficult and inflexible (Davison and Tingley 2011) but readily recyclable. In this way, recycling concrete elements should be prioritized over reuse. Reinforcement steel must therefore be separated from the concrete so that it could be recycled and the concrete could be crushed and used as a roadbed or as aggregates (Nakajima et al. 2005)

Moreover, the use of prefabrication and demountable connections must be considered right from the design brief stage. This is to allow ample time for making right decision in achieving design for deconstruction. As such, BIM-DAS must be fully integrated with existing BIM design software to provide adequate support in decision-making. Integrating BIM-DAS into

BIM software will favour automatic capture of design parameter for building deconstruction analysis to eliminate errors caused by manually entering design parameters. In addition, integrating BIM-DAS with BIM software will leverage on current BIM capabilities such as parametric modelling, visualisation, material database, etc. to analyse and visualise the effects of design decisions on deconstruction.

BIM-DAS is intended to be adapted by industrial practitioners to suit their design for deconstruction needs. In this way, BIM-DAS will be useful from the concept design stage (RIBA work stage 2) to the technical design stage (RIBA work stage 4) for measuring the deconstructability of a building. Future research will involve further refinement and implementation improvement on the prediction potentials of BIM-DAS. It is anticipated that BIM-DAS will be institutionalised with the national BIM implementation programme and guidelines. Achieving this will boost the incorporation of BIM-DAS into the construction practice.

7 Conclusion

This study describes the development of BIM-DAS score as an objective measure of degree of building deconstructability during design. This was done using a mathematical modelling approach based on the building design’s bill of quantity. In addition, the study examines and compares the BIM-DAS score of three case studies of a building model with primary material of steel, timber and concrete structures. The results identify the use of prefabricated building elements and the use of demountable connection as the key factors to be considered in designing for deconstruction. The contribution of this study is therefore three-fold: (i) it creates awareness on the roles of design in building deconstruction; (ii) it broadens the understanding of how design factors influence deconstruction; and (iii) it provides BIM-DAS score as an objective measure of deconstructability of building models. The BIM-DAS score provides a basis for comparative analysis of building models for selecting the most deconstructable design among options without affecting building forms or function. In addition, the BIM-DAS score could drive a guideline or benchmark for monitoring building construction towards end of life sustainability. The results of this study also help to understand how BIM functionalities could be employed to improve the effectiveness of existing CDEW management tools and BIM software.

Existing literature shows that design for deconstruction is more complex than material specification and that there are other factors that could influence it. However, the procedure demonstrated in this paper shows the practicality of objectively measuring the degree of building deconstructability. Further studies are needed to consider more categories of factors such as material handling, building design methodology, etc. and to assess the residual performances of building elements. Further research could also investigate the correlation between BIM-DAS and other building scores such as BDAS, CONQUAS and BWAS. While this study has been focused and biased towards deconstructability, the relationship between BIM-DAS and other building performance indicators (such as cost, sustainability, etc.) could be explored by future studies. Lastly, assuming equal weighting for model parameters seems impractical. A quantitative survey research is therefore needed to understand the weighting of parameters of BIM-DAS. This will help to understand to what extend each of the factors contributes towards the BIM-DAS of a building. To ensure the usability of the model, further studies are needed to integrate BIM-DAS into existing BIM software such as Autodesk Revit as a plugin to enable deconstruction performance simulation.

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