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# Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy

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ABSTRACT

Despite the relevance of building information modelling for simulating building performance at various life cycle stages, Its use for assessing the end-of-life impacts is not a common practice. Even though the global sustainability and circular economy agendas require that buildings must have minimal impact on the environment across the entire lifecycle. In this study therefore, a disassembly and deconstruction analytics system is developed to provide buildings' end-of-life performance assessment from the design stage. The system architecture builds on the existing building information modelling capabilities in managing building design and construction process. The architecture is made up of four different layers namely (i) Data storage layer, (ii) Semantic layer, (iii) Analytics and functional models layer and (iv) Application layer. The four layers are logically connected to function as a single system. Three key functionalities of the disassembly and deconstruction analytics system namely (i) Building Whole Life Performance Analytics (ii) Building Element Deconstruction Analytics and (iii) Design for Deconstruction Advisor are implemented as plug-in in Revit 2017. Three scenarios of a case study building design were used to test and evaluate the performance of the system. The results show that building information modelling software capabilities can be extended to provide a platform for assessing the performance of building designs in respect of the circular economy principle of keeping the embodied energy of materials perpetually in an economy. The disassembly and deconstruction analytics system would ensure that buildings are designed with design for disassembly and deconstruction principles that guarantee efficient materials recovery in mind. The disassembly and deconstruction analytics tool could also serve as a decision support platform that government and planners can use to evaluate the level of compliance of building designs to circular economy and sustainability requirements.



## 1. Introduction

There have been a lot of research work directed towards all aspect of sustainability in construction and other industrial processes (Azhar et al., 2011; Preston, 2012). For example, residential building related social sustainability assessment framework was developed in Ahmad and Thaheem (2017), a methodology to account for the systematic trade-offs between the effect of the economic, environmental, and social aspect of sustainability on the supply chain decisions is presented in Alireza et al. (2017). The building information modelling (BIM) in combination with leadership in energy and environment design (LEED) green building rating system has been pointed out as a suitable synergy to facilitate the realisation of various dimensions of sustainability (Wu and Issa, 2014; Chong et al., 2017). However, the world economy has been mostly based on a linear model of resources consumption (Su et al., 2013; Reh, 2013). This is a 'take-make-consume and dispose' pattern of economic development that relies on the belief that

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materials are always abundant and are easy to obtain and inexpensive to dispose of (COM, 2014).

The construction industry's activities according to Gencel et al. (2012), generate significant effect on the economic, environmental and social dimensions of sustainability. These activities have generated employment opportunities, provides required facilities to meet human being's need and contributed to the gross domestic product of nations (Smol et al., 2015). Notably, the construction industry has been highlighted for producing the largest amount of construction and demolition waste globally (Won and Cheng, 2017; Lawson, 2016; DEFRA, 2015; Clark et al., 2006). The resultant effect of the waste generation activities of the construction industry on the environment has been identified to include greenhouse gas and carbon emission, landfill depletion, embodied energy and raw materials wastage as well as costs overrun (Tam, 2008; Lieu et al., 2011; Wang et al., 2014; Ajayi et al., 2017).

Although design stage has been identified as the best point to tackle construction and demolition wastes (Ekanayake and Ofori, 2004), strategies for actual waste minimisation and what is required of designers and engineers are unclear (Ajayi et al., 2017). A proactive strategy is therefore, imperative to tackle the challenge of construction and demolition waste generation. Such approach will be required at the design stage of the construction process. Akinade et al. (2015) developed a BIM-based deconstruction assessment score for evaluating the level of building deconstruction that a building design supports. Though the work provides end-of-life information at the design stage, it however does not provide the architects and design engineers with alternative design choices. A system for estimating and planning demolition and renovation waste based on BIM paradigm was developed in Cheng and Ma (2013). The system provided a platform for estimating the amount of waste that a building will produce after a renovation or a demolition work. However, the study only provides support for waste management after renovation and demolition work. The present work therefore improves upon previous works by providing a disassembly and deconstruction analytics system that allows the architects and design engineers to evaluate the end-of-life performance of building designs and make necessary adjustments.

The Disassembly and Deconstruction Analytics System (D-DAS) development involves a process of using the information modelling paradigm to create decision support tools for efficient end-of-life sustainability performance of buildings. The main goal of D-DAS is to ensure efficient materials choice during design to facilitate effective material use and reduce the end-of-life waste in the built environment. Efficient materials use and reuse to minimise the introduction of new materials into the economic process is the key goal of the circular economy (Douglas, 2016; COM, 2014).

The increase in the requirement for the implementation of Building Information Modelling for different purposes, particularly for the performance analysis of building, estimation of cost, 3-D visualisation, and simulation, shows that useful invention in the built environment and construction industry must be integrateable to existing BIM platforms (Ilhan and Yaman, 2016; Akinade et al., 2017). However, the present BIM software lacks the capacity to integrate end-of-life sustainability performance analysis into building design and construction process.

This study therefore, provides this capability for BIM software by developing a disassembly and deconstruction analytics system for integrating end-of-life performance analysis into building design and construction process. The objectives are:

i. To design a D-DAS architecture for managing end-of-life concerns of buildings.
ii. To implement D-DAS within BIM software environment.
iii. To test the implementation and evaluate the system with different scenarios of a case study design.

The organisation of this paper is as follows: Section 2 contains the literature review, where practices that influence design decision in support of material use and reuse in a circular economy are identified. A detail explanation of the methodology is presented in section 3 where components of D-DAS architecture are described. Section 4 offers the implementation and evaluation of the D-DAS. Section 5 includes the discussion of the results while the conclusion and areas of further work are presented in section 6.

## 2. Building construction in circular economy

The construction industry has been suggested to have the highest potential to support circular economy principles, including eco-friendly technologies (Smol et al., 2015). This is because the usage of waste materials from construction, demolition and other production processes drives down the construction cost and ensure the preservation of the embodied energy of materials. Abdul Nasir et al. (2017) made case for the integration of the ideals of the CE into the supply chain management's theory and practice. Using an appropriate case study, the study discussed the advantage of the adoption of the CE principle as against the linear systems in terms of reduction in emissions such as carbon and nitrogen oxides. The principle and idea of CE is not new (Douglas, 2016; Su et al., 2013), but it was the July 2014 European Union communication on “zero waste programme for the Europe” which emphasised the need for its adoption (COM, 2014) that brought it to the front burner of research activities. Govindan and Hasanagic (2018) in their study of factors impacting circular economy shows that governmental viewpoint among various stakeholders has the highest influence on the circular economy principles' implementation. In a CE, it is guaranteed that materials derived values are kept in the economy for an extended period to lessen the amount of waste being transferred to landfill, thereby improving the sustainability of the environment and the business (Van Loon and Van Wassenhove,

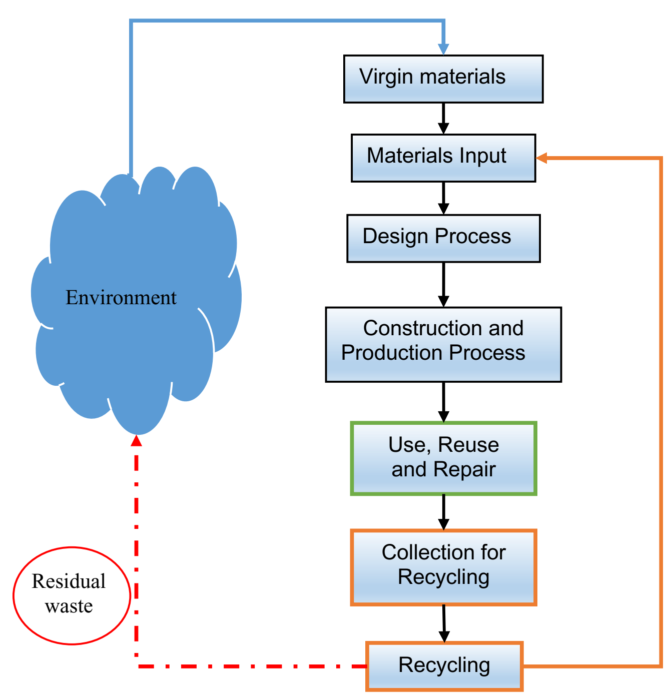


**Fig. 1.** Different stages of material life cycle in a circular economy.

2017). Fig. 1 depicts stages that materials pass through in a typical circular economy model. Each of the stages presents opportunities to reduce dependence on natural resources and costs. The primary goal in a CE is to make sure that maximum utility is obtained from materials through recycling and direct reuse. Thus, ensuring that the amount of residual waste generation is reduced (Pan et al., 2015; Tukker, 2013).

Following from the adoption of 3D BIM by the government of the UK, effective from 2016 and the European Union's zero waste strategy for Europe. Developing an architectural framework for a BIM-based system to manage the end-of-life performance of buildings during the design and construction stages presents an unprecedented opportunity to support the principles of the circular economy.

Recovery of a good proportion of building materials for the purpose of recycling and direct reuse is a major step towards a successful transition to the CE (Pan et al., 2015; Tukker, 2013). The recovery activity ensures that the introduction of new raw materials into the economy is reduced and also guarantees that the amount of materials that are disposed of as waste to landfill is minimised. Some of the studies that have contributed to the design and construction of buildings with focus on end-of-life concerns are presented in Table 1 and discussed accordingly. The works are examined for their support for the circular economy through provision of techniques and strategy to ensure materials reuse and waste minimisation.

Design for disassembly principle was presented as an alternative to practices of linear movement of materials in the built environment (Crowther, 2005; Rios et al., 2015; Guy and Ciarimboli, 2008). In design for disassembly, the linear movement of materials is replaced with a cyclic movement. The principle of whole building reuse, building component reuse and building materials recycling was proposed in the cyclic movement of materials. Kibert (2003) identified factors that inhibit closing of materials loop in the construction industry and canvassed deconstruction as an alternative to demolition to achieved effective material recovery. Tingley and Davison (2011) outlined the importance of the whole-life approach to building sustainability and emphasised consideration for the reduction of embodied energy through materials reuse. Barriers to design for deconstruction and materials reuse were identified and corresponding strategies to encourage design for deconstruction practice were identified.

Other works have also advocated for practices in the built environment that encourage easy deconstruction of buildings to support material reuse and recycling (Oyedele et al., 2014; Ajayi et al., 2015; Akinade et al., 2016). A BIM-based deconstruction assessment score to evaluate the effectiveness of waste minimisation through deconstruction was developed by Akinade et al. (2015). Tingley and Davison (2012) presented a methodology for the life cycle evaluation of the environmental impact of the design for deconstruction approach to building design and construction. The methodology was the basis for a tool named *Sakura* for calculating the embodied energy in building components. However, Sakura is implemented as a web service without BIM capability and as such cannot be used to effectively support designers and engineers using BIM software. The essential functionalities required of BIM-based deconstruction is enumerated in Akinade et al. (2017). Chief among the requirements is the accessibility to design for deconstruction strategy within BIM platforms. Integration of the process of product design and disassembly for easy materials recovery for economic purposes was the focus of the study in Johnson and Wang (2010).

## 3. Methodology

An architecture that is meant to be implemented across multiple software platforms needs to avoid over-complication (Garlan et al., 2009). The D-DAS architecture is an assemblage of different layers, views and components that make up the system and the description of relations and interaction amongst them, loosely coupled in line with Garlan and Shaw (1994). The loosely coupled nature of the architecture ensures that the implementation can commence at once on all the components and layers (Long et al., 2012).

### 3.1. Disassembly and deconstruction analytics system architecture

The global view of the proposed D-DAS architecture is presented in Fig. 2. The architecture is composed of four layers namely: (i) Data storage layer, (ii) Semantic layer, (iii) Analytics and functional model layer and (iv) Application layer. The four layers are logically connected to function as a single system. The interaction of the users with the system is through the application layer.

### 3.2. Data storage layer

The data storage layer contains storage for three categories of data. (i) building design information, (ii) building materials specification information and (iii) building deconstruction and demolition data. The first two categories of data are required for effective functioning of D-DAS while the third category of data is required for initial analytics and machine learning model development. The building design information includes parametric models of building, materials specification for building construction and material quantity take-offs. This design information is obtainable from BIM models of the building. The building materials information include material properties such as density, dimension, status (i.e. new,

**Table 1**
Previous works that contribute to building design with focus on end-of-life.

| SN | Techniques Advocated | Reference | BIM Compliant | Implementation |
|---|---|---|---|---|
| 1 | Design for Disassembly | Crowther (2005) | ✗ | ✗ |
| 2 | Prefabrication and life cycle design | Jaillon & Poon (2014) | ✗ | ✗ |
| 3 | Building deconstruction and material recovery | Saghafi & Teshnizi (2011) | ✗ | ✗ |
| 4 | Material reuse through design for deconstruction | Tingley & Davison (2011) | ✗ | ✗ |
| 5 | Material reuse through design for deconstruction | Guy et al. (2006). | ✗ | ✗ |
| 6 | Design for deconstruction for environmental benefits and life cycle assessment | Tingley & Davison (2012) | ✗ | ✓ |
| 7 | Critical success factors for diverting waste from landfills | Akinade et al. (2016) | ✓ | ✗ |
| 8 | Design for Disassembly and Deconstruction | Rios et al. (2015) | ✗ | ✗ |
| 9 | Waste minimisation by deconstruction | Akinade et al. (2015) | ✓ | ✗ |
| 10 | DfD: Design for Disassembly in the Built Environment | Guy and Ciarimboli (2008) | ✗ | ✗ |
| 11 | Deconstruction: The start of a Sustainable materials strategy through deconstruction | Kibert (2003). | ✗ | ✗ |
| 12 | Designing structural systems for deconstruction. | Webster and Costello (2005) | ✗ | ✗ |
| 13 | Essential functionalities of a BIM-based deconstruction tool | Akinade et al. (2017) | ✓ | ✗ |

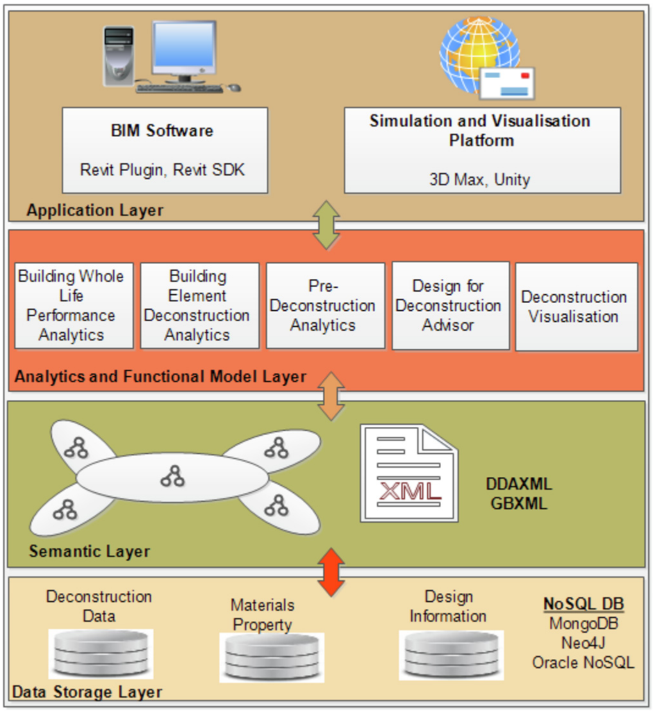


**Fig. 2.** Disassembly and deconstruction analytics system (D-DAS) architecture.

reuse or recycled). The demolition data contains historic data of deconstructed buildings. This includes information about building properties and corresponding demolition wastes and recoverable materials.

The building design information is required for the processes that take place at the analytics and functional model layer where building design is analysed to determine the degree of disassembly and deconstruction that building designs support at the end-of-life. This data also serves as input to the demolition arising analytics process. The historic demolition data and building materials information are required for developing the predictive and prescriptive analytics models for the purpose of analysing building design for circular economy support. The data storage layer provides the facility to keep this variety of data. Because of the diverse nature and variety of data that will be stored by the storage facility, a NoSQL database is proposed for the implementation of the D-DAS. This is because NoSQL database (such as MongoDB, Neo4J, Oracle NoSQL, etc.) provides robust and flexible means of storing varieties of data and are capable of handling structured, semi-structured and unstructured data (Neal, 2010; Han et al., 2011; Wei-ping et al., 2011).

### 3.3. Semantic layer

The Semantic layer of D-DAS architecture provides two functionalities. These are (i) data exchange formatting and (ii) data provisioning to the application layer. The data exchange formatting provides a common data format for sharing building information among the modules in the system. The Deconstruction and Disassembly Analytics XML (DDAXML) is being proposed for sharing data among different modules in the system. This is an extension of an industrial supported schema for sharing building information between different BIM software i.e the green building XML (gbXML) (gbXML, 2017). The data provisioning functionality provides the application layer of the architecture with seamless access to databases through the use of Representation State Transfer (REST) web service.

### 3.4. Analytics and functional model layer

The functionalities of D-DAS are developed at the Analytics and Functional layer of the architecture. In the layer, there are five analytics and functional models namely: (i) Building Whole Life Performance Analytics (ii) Building Element Deconstruction Analytics (iii) Deconstruction Arising Analytics (iv) Design for Deconstruction Advisor and (v) Deconstruction Visualisation. These models are discussed in the following subsections.

#### 3.4.1. Building Whole Life Performance Analytics

The continuous use of materials after exploration and extraction from the environment to preserve its embodied energy is the hallmark of a CE (Geissdoerfer et al., 2017; Lieder and Rashid, 2016). To ensure that building materials remain functional, it is pertinent to device means for monitoring their performance over the lifetime of the entire building. The monitoring is to ensure that building materials that can no longer function as expected in a building are removed and taken to where it will be reused in its state or recycled for other purposes. The logic of the Building Whole Life Performance Analytics (BWLPA) model is based on the Weibull distribution for manufactured product and various factors that affect the performance of building materials over time. Equation (1) shows the expression for calculating the performance of building with respect to time (Akanbi et al., 2018).

$$P = RU + RC + \gamma \tag{1}$$

From the equation, P is the performance of building over time, $RU$ is the reusable fraction of the building materials, $RC$ is the recyclable fraction and $\gamma$ is the fraction of the performance that leads to waste disposal to landfill. Equations (2) and (3) respectively further describe $RU$ and $RC$.

$$RU = \left(\beta\frac{ndc}{nc} + \lambda\frac{nfb}{ne} + \mu\frac{\nu\bar{S}f}{\nu m} + \rho\frac{\nu\bar{h}t}{\nu m}\right)\left(1 - e^{t-\alpha} - \frac{t}{10 * \alpha}\right) \tag{2}$$

$$RC = 1 - RU - \gamma \tag{3}$$

The explanation of the independent variables in equation (2) above are shown in Table 2. The corresponding variables values are obtained through the custom parameters of the BIM model of buildings being analysed for whole life performance.

#### 3.4.2. Building Element Deconstruction Analytics

The Building Element Deconstruction Analytics (BEDA) provides an assessment of the level of design for deconstruction (DfD) that a building design supports. With this module, a BIM model of a building could be evaluated to determine if the building would support deconstruction rather than demolition at the end-of-life. The BEDA model is based on the Deconstructability Assessment Score (DAS) presented in Akinade et al. (2015) where building's degree of deconstructability is determined based on key DfD factors. These factors include building element type, number of building element present in a design, connection type and prefabricated element specification in the building design. Other factors used for calculating DAS of building designs are (i) specification of reusable and recyclable materials for the construction (ii) the use of toxic materials and (iii) the use materials with secondary finishes in the construction of the building.

**Table 2**
Description of independent variables in equation 2.

| Notation | Description |
|---|---|
| $t$ | Building's age (year) |
| $nc$ | total number of connections |
| $ne$ | total number of possible building elements |
| $ndc$ | demountable connections (number) |
| $nfb$ | prefabricated assemblies (number) |
| $v\overline{S}_f$ | materials with no secondary finishes (volume) |
| $vm$ | building materials total (volume) |
| $v\overline{h}_t t$ | material with no hazardous content (volume) |
| $\alpha$ | life expectancy of building |
| $\beta$ | weighting factor for the significance of using demountable connections on reusability of building materials at the end-of-life |
| $\lambda$ | weighting factor for the significance of using prefabricated assemblies on reusability of building materials at the end-of-life |
| $\mu$ | weighting factor for the significance of specifying materials without secondary finishes on reusability of building materials at the end-of-life |
| $\rho$ | weighting factor for the significance of specifying materials without hazardous content on reusability of building materials at the end-of-life |

#### 3.4.3. *Pre-deconstruction analytics*

The Pre-Deconstruction Analytics (PA) module provides the platform for generating the Pre-Deconstruction Audit (PDA) for buildings at the end-of-life before disassembly and deconstruction. This module integrates machine learning techniques to develop the predictive model for pre-deconstruction audit generation. The PDA is part of the requirements for meeting BREEAM Wst01 construction waste management standard in the UK. The PA module contains the logic for determining the quantities of materials that are obtainable from a building after deconstruction. The development of PA module is based on the combination of historic PDA data, information obtained from PDA experts and machine learning algorithms (such as Deep Neural Network, Restricted Boltzmann Machine, Support Vector Machine, etc.) The machine learning algorithm is used to determine the correlation and pattern in the existing PDA data to predict the deconstruction arising for buildings. The PDA module divides the materials into their corresponding routes i.e. reusable, recyclable, energy recovery and landfill. In a CE, PDA presents a building as a material bank which could be used in planning. With PDA, potential markets could be identified for reusable and recyclable materials that would arise when the building is deconstructed.

#### 3.4.4. *Design for Deconstruction Advisor*

The minimisation of materials extraction and subsequent reduction in the introduction of new materials into the economy, thereby leading to the reduction in the amount of materials being sent back to the environment as wastes is the primary goal in a CE (Su et al., 2013; Pan et al., 2015; Douglas, 2016). Therefore, it is important that construction process in the circular economy follows best design and construction practices that reduce wastes at construction stage and at deconstruction/demolition stage. Design for Disassembly/Deconstruction is an important method that supports waste reduction at the buildings' end-of-life (Kibert, 2003; Crowther, 2005; Tingley and Davison, 2012; Akinade et al., 2015). The Design for Deconstruction Advisor (DfDA) module examines the building design to identify possible building elements and materials that could be optimised to support waste reduction and materials reuse. The module uses the deconstructability assessment score to evaluate building design and provides alternative design specifications and materials selection for effective end-of-life performance.

In conjunction with the BEDA module, the DfDA module provides the prescriptive analysis of building design, where different combinations of factors that affect building performance in terms of deconstruction and materials recovery at the end-of-life are examined. Depending on the building requirement and prevailing circumstances, the design engineer can update the building design according to the prescription result from this module.

#### 3.4.5. *Disassembly and deconstruction visualisation*

The disassembly and deconstruction visualisation module is responsible for generating the deconstruction plan and visualisation of the deconstruction and disassembly process. Its logic is based on best practice in the UK demolition industry where the safety of both human and environment is paramount. The deconstruction protocol document which contains instructions on how to carry out deconstruction of buildings is generated by this module. The visualisation platform regenerates the 3D model of buildings with different categories of materials obtainable identified. Based on the deconstruction protocol, the simulation of deconstruction and disassembly process for the building is produced by this module. This output will assist demolition engineers to get insight into the building and the points to begin the deconstruction and disassembly of the building elements. It will provide visualisation of different materials that could be recovered from the building and their possible routes (reusable, recyclable, energy recovery and landfill).

### 3.5. *Application layer*

The application layer provides platforms through which the functionalities of D-DAS are made available to the users. It is the implementation and integration of various modules in the analytics and functional model layer of the architecture. The D-DAS is implemented in two ways. The first implementation is the Plug-in for the existing BIM software, e.g. Revit. D-DAS implementation as Revit Plug-in is developed with the use of Revit 2017 SDK and Visual C# programming language. The second implementation of D-DAS functionalities is a standalone application that is based on simulation and visualisation tools such as 3D Max, Unity, Unreal, Maya, Stingray etc.

The plug-in implementation of D-DAS extends the functionalities of the existing BIM software to provide design support for Architects and design Engineers in respect of the buildings' end-of-life performance. It also provides support for site waste management planners in generating the Pre-demolition audit report from the BIM model of buildings. The standalone implementation of D-DAS functionalities provides visualisation platform to support the designers during the building design process and demolition Engineers during the demolition stage of the building.

## 4. System implementation and evaluation

Two approaches have been identified for the implementation of the disassembly and deconstruction analytics system. The first approach is the integration of D-DAS functionalities to the existing BIM software as a plug-in and the second approach is the implementation of the simulation and visualisation functionalities of D-DAS as a standalone visualisation platform. The standalone implementation of D-DAS is based on simulation and game engine software (i.e. 3D Max and Unity). However, this is not the scope of the present work (see Fig. 3 for the scope of this work).

The introduction of BIM for the construction process has revolutionised the activities across the industry, and its adoption by construction companies is arguably on the increase (Volk et al., 2014; Arayici et al., 2011). Therefore, to leverage on the opportunity provided by BIM, D-DAS is implemented as a plug-in for Autodesk Revit. The D-DAS functionalities implemented in this work are (i) Building Whole Life Performance Analytics (ii) Building Element Deconstruction Analytics and (iii) Design for Deconstruction Advisor. Fig. 4 shows the D-DAS plug-in interface in Revit.

With D-DAS plug-in, the Architects and design Engineers will be able to evaluate building design for whole life performance and design for disassembly and deconstruction support. The plug-in also provides alternative design specifications that support better end-of-life performance of buildings. The parameters required by D-DAS plug-in are made available with the BIM model of building with the use of custom parameter specification in addition to standard parameters of the model. The interface for specifying these custom parameters within Revit software is shown in Fig. 5.

### 4.1. System evaluation with case study

To test and evaluate the performance of D-DAS, a case study design of an office building that contains three-floor levels was used. The building is located in the southwestern part of the UK. Different design parameters and materials specification for the structural components of the building were used to obtain three scenarios from the building design. The case study building's features are presented in Table 3 while the inventory of materials for the three design options is shown in Table 4. The floor plan is presented in Fig. 6. The 3D model and materials specification for the case study building was prepared in Autodesk Revit 2017 software.

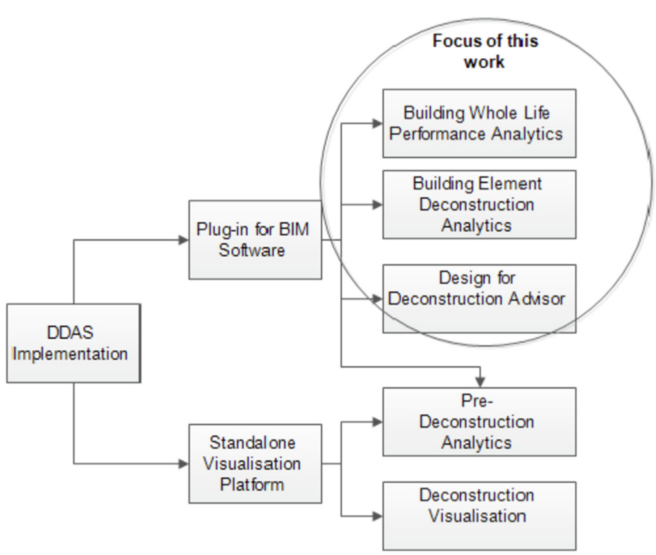


**Fig. 3.** Implementation framework for D-DAS showing focus of this work.

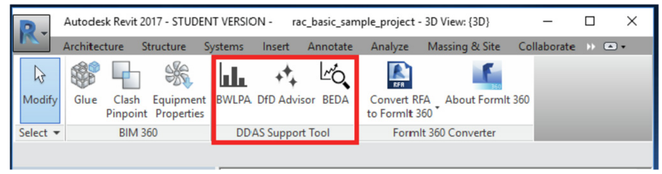


**Fig. 4.** D-DAS implementation plug-in in Autodesk Revit 2017

The D-DAS plug-in was used to evaluate the building design for end-of-life performance. Table 5 shows values for the required input to the BEDA and BWLPA models and result for each of the three building design scenarios. Fig. 8 shows the summary of the results of the three scenarios. The result of the whole-life performance evaluation of designs with respect to the amount and number of recoverable materials over time have been presented earlier in Akanbi et al. (2018). Fig. 7 provides the design for deconstruction advisor through which the effects of various material and design choice made on the end-of-life waste performance of the designs are examined. In the design for deconstruction advisor, the effect of different materials selection on the overall waste output is shown on the leftmost pane. This platform provides the means for architects and design engineers to trial various combinations of materials on different building component and select a combination that is optimised for the end-of-life performance.

## 5. Discussion

The D-DAS implementation framework presented in this work provides a system architecture that BIM software developer could use to incorporate building deconstruction and materials recovery functionalities into BIM software for the construction industry. This is to enable architects and design engineers to evaluate building designs for end-of-life sustainability performance. The system leverages the BIM capabilities to provide a platform that supports the evaluation of end-of-life performance behaviour during the design process. The capability that is leveraged is the ability to incorporate all information related to buildings' functional and physical features, and project life cycle into a building design model.

The implementation of D-DAS as a plug-in enables building designs to be evaluated for end-of-life performance. For instance, evaluating the case study design for whole life performance shows the recoverability curves for the building over time. The result of the analysis shown in Table 5 depicts deconstructablity assessment score (DAS) of 0.94, 0.61 and 0.57 for building design with steel, timber and concrete structures respectively. This implies that building with steel structure has the highest level of support for disassembly and deconstruction based on end-of-life evaluation. Next to steel structure is the building with timber structure and then the building with concrete structure which has the least support for disassembly and deconstruction. The results of the building design's whole life assessment confirm that demountable connections within steel buildings generate more reusable materials at the end-of-life. On the other hand, the design with the timber structure generates end-of-life materials that are 65% reusable and 35% recyclable while the design with the concrete structure produces end-of-life materials that are 42% reusable and 58% recyclable. These results are in line with findings in Akinade et al. (2015) and Akanbi et al. (2018). In addition to the affirmation of results from previous works, the design for deconstruction advisor platform provides design evaluation functionality, where designs could be attuned to achieve the required end-of-life performance benchmarks. Cheng and Ma (2013) developed a system

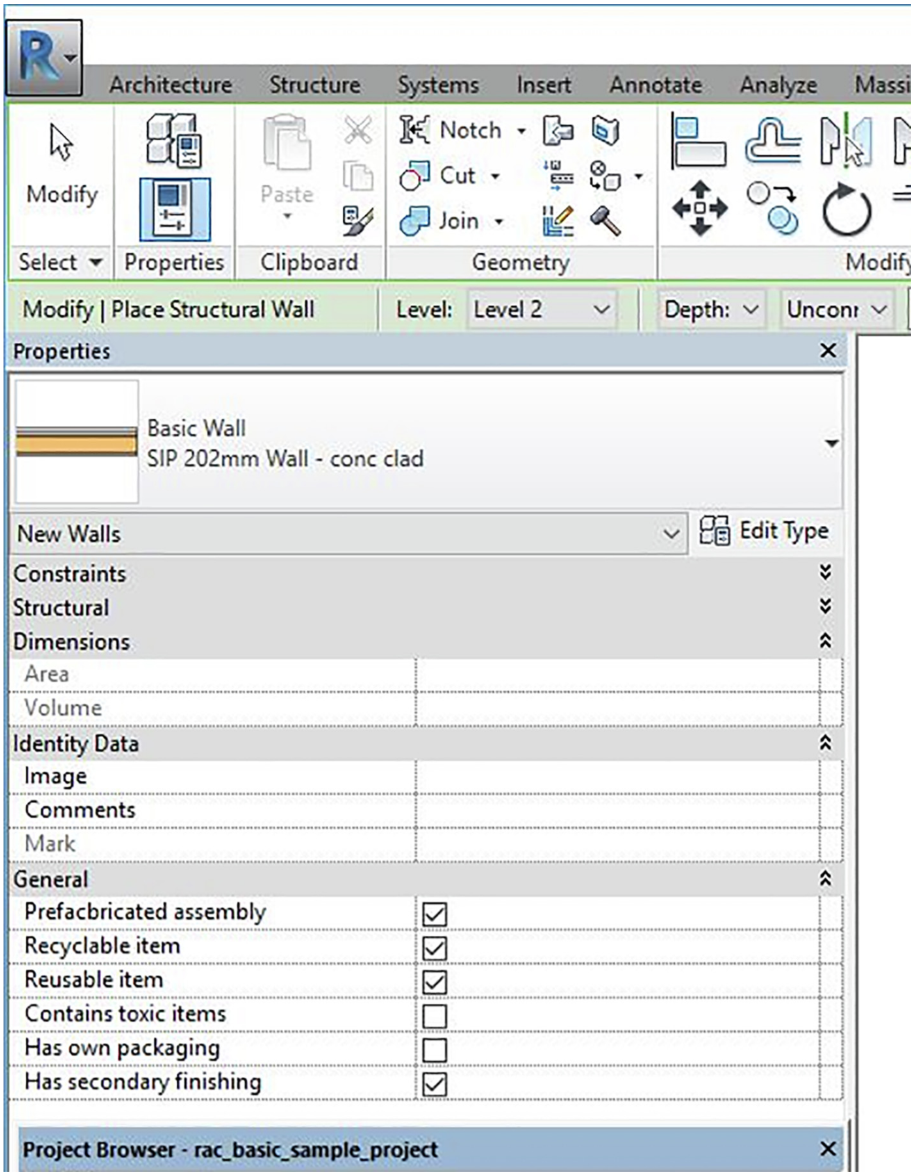


**Fig. 5.** Custom parameter specification interface in Revit.

**Table 3**
The case study Building's features.

| Feature | Value |
|---|---|
| Type of building: | Office |
| Floors: | 3 |
| Area of the ground floor | 492 $m^2$ |
| Area of the 1st floor | 351 $m^2$ |
| Area of the 2nd floor | 351 $m^2$ |
| Height of the floor to ceiling | 2.8 m |
| Area of the 2nd floor roof | 402 $m^2$ |
| Area of the low level roof: | 168 $m^2$ |

for estimating demolition and renovation waste which provide similar functionality as pre-deconstruction analytics of the D-DAS system. While Cheng and Ma (2013) is about waste management when the waste has already occurred, the D-DAS tool tackles waste problems at the design stage before wastes occur.

The following subsections discuss the use of D-DAS for reusability, recyclability and recoverability assessment of the three scenarios of the building design. The Design for Disassembly/Deconstruction module provides the platform for designers to examine the effect of using a material type in a particular building element. With this functionality, the choice of materials for construction could be maximised in such a way that both construction and deconstruction wastes are minimised. The module computes the deconstruction assessment score of the building design based on DfD factors. The analysis of the amount of materials in building elements is generated by this module.

### 5.1. *D-DAS for reusability assessment of building design*

Using D-DAS Revit plug-in to evaluate building design for end-of-life performance produces results as shown in Table 5 and Fig. 8. For comparison, Fig. 8 shows the performance of the three scenarios of the building design. The blue curve depicts the performance of building design with a steel structure, the green curves depict the performance of building design with a timber structure and the curves in magenta colour depict the performance of the

**Table 4**
Material inventory for the case study building design options.

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

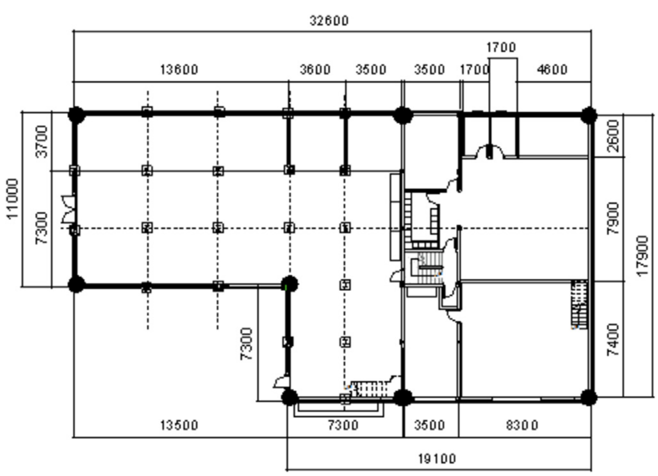


**Fig. 6.** Case study Building's floor plan.

building design with a concrete structure. The recoverability curve (shown in red) shows the amount of building material that is recoverable with respect to time. From the figure, building with steel structure produces the highest reusable materials (93% of total recoverable) followed by building with timber structure (65% of total recoverable). Building with concrete structure produces the lowest reusable materials (42% of total recoverable). These results are in line with the finding of other researchers. For example, the poor performance of concrete structure in terms of reusability is because it is mostly impossible to disassemble concrete structure without damage (Tingley and Davison, 2012; Akinade et al., 2015). Therefore, concrete structures are better recycled by crushing and then reuse as roadbed or aggregates in new constructions (Nakajima et al., 2005).

### 5.2. D-DAS for recoverability assessment of building design

The materials recoverability curve shown with red colour in Fig. 8 is centred on the Weibull distribution. The formula is the most commonly used probability distribution function to describe the behaviour of products in terms of reliability over their lifetime (Xie and Lai, 1996; Almalki and Yuan, 2013). The curve presents the expected degradation in the functional performance of the building materials as a result of normal operation of the building. This approach to materials degradation estimation has been adopted in this study because it is difficult to know the exact usage and environmental factors that the building will be subjected to.

## 6. Conclusion

This study presents the system architecture and the associated implementation of Disassembly and Deconstruction Analytics System that employs design-centric and information-centric capability provided by BIM. A layered approach to system architecture development was adopted for D-DAS architecture. There are four layers in the system architecture namely: data storage layer, semantic layer, analytics and functional model layer and application layer. The storage layer provides information storage capabilities required for the system to function efficiently. Because of the varying nature of the information (e.g. building design, material specification, materials information, etc.) to be stored in the data storage, a NoSQL database has been identified for the implementation of the storage component of D-DAS. The semantic layer provides the analytics and functional models layer seamless access to the database through the use of DDAXML. The information in the database is transformed into a form that the models in the analytics and functional models layer can understand and use for various processing. The application layer provides the interface through which the functionalities of D-DAS are made available to the users.

**Table 5**
Result of D-DAS evaluation of the building scenarios.

| Scenarios | ***nfb*** | ***ndc*** | ***ne*** | ***nc*** | $v\bar{h}t$ | $v\bar{S}f$ | ***vm*** | DAS | $S_{ru}$ | $S_{rc}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Concrete | 0.00 | 20.00 | 64.00 | 256.00 | 8000.00 | 8000.00 | 10000.00 | 0.57 | 0.42 | 0.58 |
| Timber | 40.00 | 20.00 | 64.00 | 256.00 | 10000.00 | 9000.00 | 10000.00 | 0.61 | 0.65 | 0.35 |
| Steel | 64.00 | 206.00 | 64.00 | 256.00 | 10000.00 | 9000.00 | 10000.00 | 0.94 | 0.93 | 0.07 |

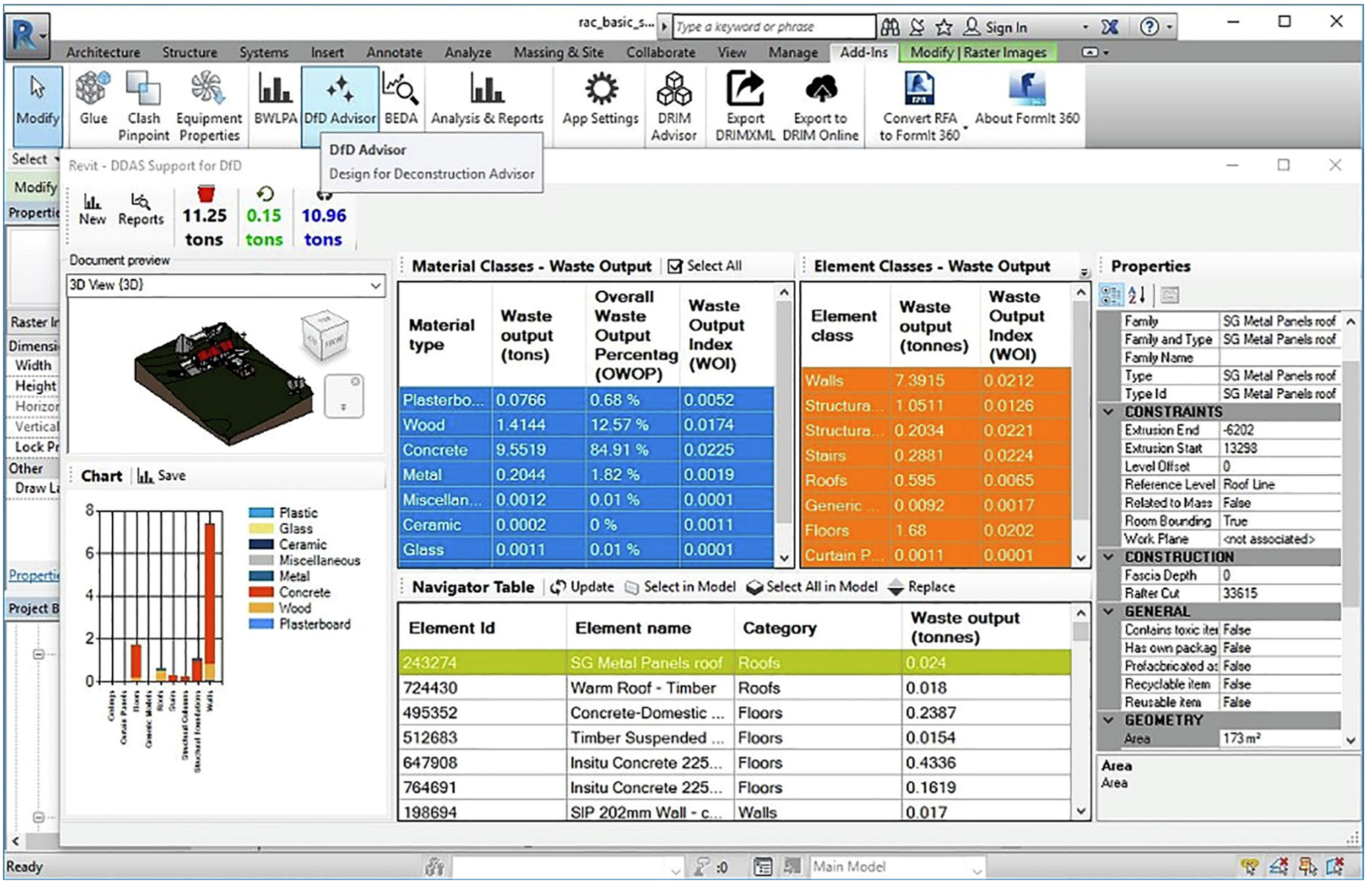


**Fig. 7.** Design for deconstruction advisor implementation in Autodesk Revit 2017.

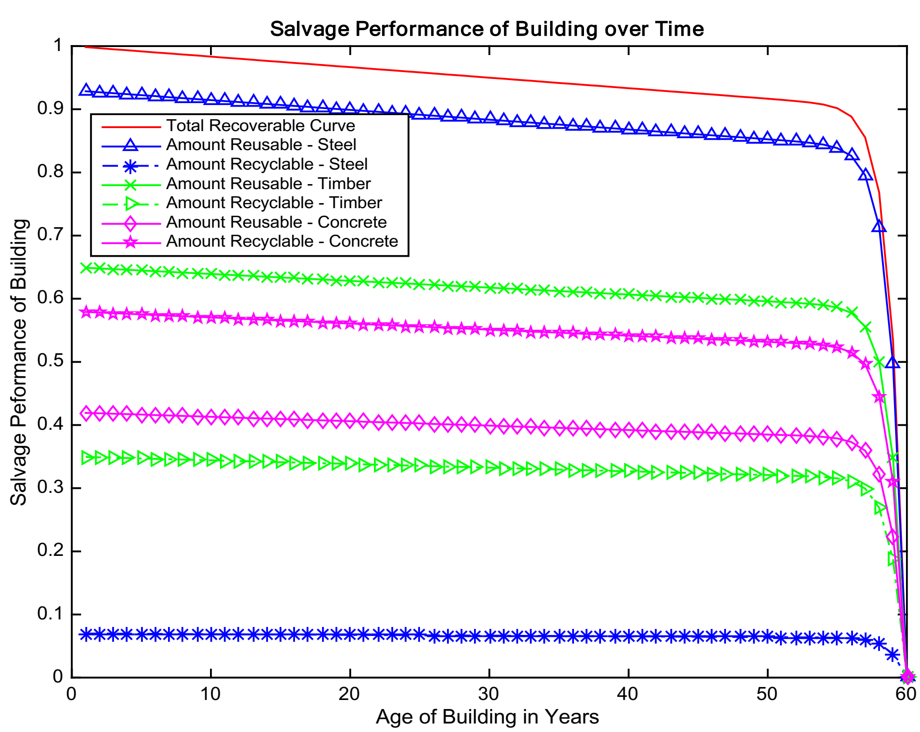


**Fig. 8.** Comparative analysis of performance of the three scenarios of the case study.

The implementation of D-DAS as a plug-in for Revit software has also been presented. The plug-in, named D-DAS solution provides a platform for architects and design engineers to assess building designs for end-of-life performance. Building Whole Life Performance Analytics, Building Element Deconstruction Analytics and DfD Advisor are the functionalities that D-DAS solution plug-in provides. With D-DAS plug-in, building design can be assessed for end-of-life performance especially with respect to the circular economy goal of ensuring little or no new materials are introduced into the economy. The DfD advisor provides the analysis of the effect of design and material choice on the building end-of-life performance in terms of waste generation.

Therefore, two major contributions have been identified from this study: (i) design of a system architecture for evaluating building design for performance analysis of the end of the life situation. (ii) provision of a Building Information Modelling support platform for assessing buildings designs' level of compliance with the circular economy principles and objective. This ensures material reuse, reduction in the waste generation to landfill and reduction in raw materials extraction from the environment.

The academic implication of this study lays bare the understanding of how results of various academic works in waste minimisation could be implemented and transformed into a practical software system that is useful to construction industry practitioners. The implication for practice is hinged on the need for the adoption of BIM to maintain a lead in the changing and highly competitive construction industry. Therefore, this study incorporates disassembly and deconstruction analytics into BIM software to support building designers and engineers. The acceptability and usability of D-DAS tool among industry practitioners will be enhanced through its accessibility from within BIM software environment. Also, providing detail architecture and implementation procedure of D-DAS will make it possible for BIM software developers to integrate the solution into the future versions of their product.

The building whole life performance analytics model of D-DAS uses the material durability and building life expectancy presented by the British Standard Institute (BS7543:2015). This is however purely theoretical. Efforts will therefore be made in the future to use quantitative approaches to estimate quantities of recoverable building materials at the end-of-life.

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