Resources, Conservation & Recycling 129 (2018) 175–186

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full Length Article

Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator

Lukman A. Akanbi[a], Lukumon O. Oyedele[a,*], Olugbenga O. Akinade[a], Anuoluwapo O. Ajayi[a], Manuel Davila Delgado[a], Muhammad Bilal[a], Sururah A. Bello[b]

[a] Bristol Enterprise, Research and Innovation Centre (BERIC), Bristol Business School, University of the West of the England, Bristol, United Kingdom
[b] Department of Computer Science and Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria

A R T I C L E I N F O

Keywords:
Building information modelling (BIM)
Whole-life performance profile
Building materials
End-of-life
Circular economy

A B S T R A C T

The aim of this study is to develop a BIM-based Whole-life Performance Estimator (BWPE) for appraising the salvage performance of structural components of buildings right from the design stage. A review of the extant literature was carried out to identify factors that influence salvage performance of structural components of buildings during their useful life. Thereafter, a mathematical modelling approach was adopted to develop BWPE using the identified factors and principle/concept of Weibull reliability distribution for manufactured products. The model was implemented in Building Information Modelling (BIM) environment and it was tested using case study design. Accordingly, the whole-life salvage performance profiles of the case study building were generated. The results show that building design with steel structure, demountable connections, and prefabricated assemblies produce recoverable materials that are mostly reusable. The study reveals that BWPE is an objective means for determining how much of recoverable materials from buildings are reusable and recyclable at the end of its useful life. BWPE will therefore provide a decision support mechanism for the architects and designers to analyse the implication of designs decision on the salvage performance of buildings over time. It will also be useful to the demolition engineers and consultants to generate pre-demolition audit when the building gets to end of its life.

1. Introduction

The construction industry generates the largest percentage of the total waste all over the world (Clark et al., 2006). In the UK alone, Construction and Demolition Waste (CDW) is an average of 45.8 million tons annually with 85% of it being recovered (Lawson, 2016; DEFRA, 2015). The case is not different in other developed countries like the United States, Australia, and Germany, etc. In the United States and Australia, the amount of CDW annually is about 534 million tons (USEPA, 2016) and 19 million tons (Hyder Consulting, 2011) respectively. According to Kibert (2008), 50% of the entire waste generated by the construction industry worldwide is due to end-of-life activities, which are primarily demolition. This is because buildings are often disposed at the end of their useful life where the potential of material reuse is sometimes impossible. Although the recycling of entire building is becoming popular, a more beneficial use of recovered building material is direct reuse. This is because materials reuse requires minimal energy usage as compared to the energy needed for material recycling (Addis, 2006). It is based on this that building deconstruction is becoming more preferred over demolition because of its economic and environmental benefits (Coelho and de Brito, 2011).

Building deconstruction is a practice that supports the concept of circular economy (CE) model. The CE model, which is being adopted by developed and emerging economies of the world, has led to the creation of markets for recovered materials from CDW (COM, 2014). CE is a sustainable development strategy that aims at improving the efficiency of materials and energy usage. This is a paradigm shift from the existing linear economy model of "take-make-consume and dispose" to a more sustainable model of "take-make-consume-reuse and recycle" (Douglas, 2016; COM, 2014). The desire for circular economy and optimal material reuse calls for the need to improve techniques for whole-life performance assessment of buildings. As such, it is important to develop performance profile for buildings to know the best time its optimal salvage value could be obtained. Therefore, to achieve an effective whole-life performance assessment of buildings, performance characteristics of individual building components must be taken into

* Corresponding author at: Bristol Enterprise, Research and Innovation Centre (BERIC), Professor and Chair in Enterprise and Project Management, Bristol Business School, University of the West of England, Bristol, Frenchay Campus, Coldharbour Lane, Bristol, BS16 1QY, United Kingdom.
E-mail addresses: Ayolook2001@yahoo.co.uk, L.Oyedele@uwe.ac.uk (L.O. Oyedele).

http://dx.doi.org/10.1016/j.resconrec.2017.10.026
Received 4 May 2017; Received in revised form 2 October 2017; Accepted 21 October 2017

consideration (Wordsworth and Lee, 2001). Accordingly, the individual performance profile of building components will provide a pointer to the overall performance of the building over a given time. This approach will therefore be useful at the design stage to identify the types and volume of recoverable materials that are reusable, recyclable, and those that must be sent to landfill (Thormark, 2006).

Pointedly, the recent paradigm shift to design-centric and information-centric approach to building construction has favoured the adoption of Building Information Modelling (BIM). The benefits of BIM have made many countries to set deadlines for its adoption in their construction industry. Thus, the deadlines have forced most companies to integrate BIM into their activities to sustain their competitive advantage (Coates et al., 2010; Succar and Kassem, 2015). The rise in BIM implementation for diverse needs, especially for 3D building visualisation, building performance analysis, cost estimation, facility management, reveals that genuine innovation within the construction industry must be BIM compliant. The Building Research Establishment (BRE) developed a specification and database named Integrated Material Profile And Costing Tool (IMPACT) with the overall aim of integrating Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and BIM (BRE, 2017). Presently, there are three IMPACT compliant tools namely: IES, eToolLCD and One Click LCA (IMPACT, 2017). These tools are used to carry out sustainability assessment, environmental impacts and life cycle costing of buildings in accordance with sustainability standard such as BRE Ecopoints, BS ISO BRE Ecopoints, BS ISO 15686-5:2008 etc. However, these tools do not provide a whole-life assessment of building design in terms of the salvage value (i.e. reusability and recyclability of the materials) with respect to time. Also, a recent review of BIM adoption for sustainability by Chong et al. (2017) reveals that there is a significant amount of research and development on BIM usage during various project phases. However, there are only a few works on how BIM could be applied in refurbishment and demolition process.

It is on the basis of the foregoing that this study emerges. The aim of the study is to develop a BIM-based tool for forecasting the whole-life salvage performance of buildings at the design stage. The specific objectives are:

i To model the effect of time and other properties on the salvage performance of buildings.
ii To develop a BIM-based system for forecasting the salvage performance of building right from the design stage.
iii To test the model using case study design of real-life buildings.

A mathematical modelling approach with the use case study for model testing has been adopted to achieve the set objectives. Therefore, a thorough review of the related literature was carried out to identify factors that influence salvage performance of buildings. The review helps to determine the appropriate method for modelling salvage performance of building materials based on the passage of time and identified factors. Then, a mathematical model of salvage performance of buildings was developed based on these factors using the concept of Weibull reliability distribution. The model was tested using existing building as a case study.

The meaning of salvage performance as used in this study is the value of building at a particular time in terms of quantity of structural materials (in tons) that is obtainable when the building is demolished or deconstructed. This value is computed based on the bill of quantity as retrieved from BIM model of buildings using a mathematical modelling approach. The rest of the paper is organised as follows: The literature review is covered in Section 2, where factors that affect reusability and recyclability of recoverable building materials in relation to the circular economy were discussed. A detail description of the methodology and model development are covered in Sections 3 and 4. The model evaluation is presented in section 5 while discussion of the results is presented in Section 6. Section 7 ends the paper with conclusion and areas of further research.

1.1. Scope of the study

Previous work by British Chartered Institution of Surveyor (BCIS) grouped building system into six major components namely: substructure, superstructure, finishes, fittings and furnishings, services and external works (BCIS, 2006). Akinade et al. (2015) provided a modified layer approach of building system developed by Brand (1994) which comprises six layers namely: site, structure, skin, services, space plan and stuff. Developing a model that estimates the salvage performance of the whole building system is not feasible as each component/layer react is affected by different factors some of which could not be measured objectively. Therefore, the scope of this work is limited to the material analysis of the structural component of buildings. The details of the structural component for analysis are obtained from the bill of quantities as specified in the BIM model of the building.

It is also important to note that there are issues that bother on the usefulness of materials recovered from demolished/deconstructed buildings in term of reuse and recyclability. Especially, in the areas of recertification, legal warranties and residual performance of recovered building materials after several years of usage (Kibert et al., 2001). There are pieces of evidence which indicate that recovered building materials such as wood cannot be regraded but can only be used for non-structural low market applications (Falk, 2002). Bearing this in mind, this study assumes that the recoverability of building components could be determined during design and the value of building component is uniformly affected with the passage of time.

2. Circular economy in building construction

Circular Economy (CE) and sustainability concepts are continuously becoming popular among the policy makers, academia and industry (Geissdoerfer et al., 2017) and efforts have been made to establish the conceptual relationship between CE and sustainability (Nakajima, 2000; Andersen, 2007; Rashid et al., 2013). While the most widely referenced definition of sustainability defined it as "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). On the other hand, CE is defined "as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops" (Geissdoerfer et al., 2017). Based on these definitions, CE is therefore a way of achieving sustainable development. Rashid et al. (2013) describe the implementation of circular economy principle in business models and supply chains as a requirement for sustainable manufacturing for enhanced economic and environmental performance of nations. The European Commission noted that circular economic systems is of immense benefit for sustainability development across Europe and encouraged member states to adopt it (COM, 2014). To promote the concept of CE in the built environment, the Waste and Resources Action Programme (WRAP) has provided a number of good practice guidance that must be embraced by the industry. These include BIM, design out waste, design for deconstruction, offsite construction, sustainable procurement, fairness, inclusion and respect (WRAP, 2013).

According to Smol et al. (2015), one of the key industries that can benefit maximally from the development of new eco-technologies and CE is the construction industry. Although the concept of CE is not new (Su et al., 2013), it was recent that the European Union through its communication of July 2014 emphasized the need for the adoption of CE system through its zero waste programme for the Europe (COM, 2014). CE systems ensure that the added value in products is kept within the economic circle for as long as possible to avoid waste generation to landfill. Fig. 1 shows the phases of a circular economy model, with each phase presenting opportunities in terms of reducing costs and dependence on natural resources as the only source of material input to the construction and other production processes. The main objective of CE is to maximise the use of materials through collection and reuse

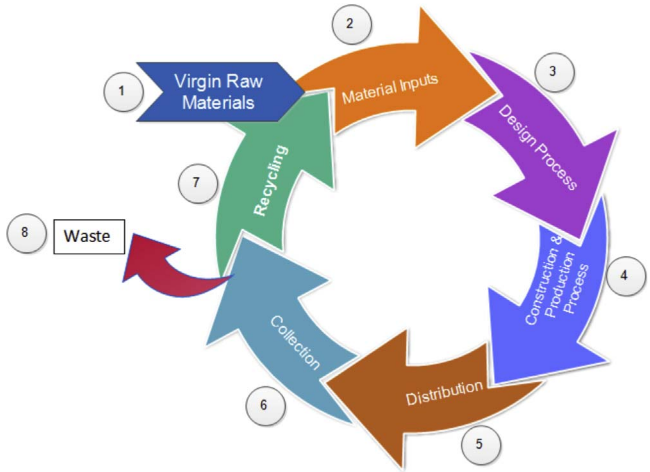

Fig. 1. Different Phases in a Circular Economy Model.

(stage 6) and recycling (stage 7). This is to reduce the amount of waste (stage 0) being generated thereby leading to a solution where everyone benefits (Pan et al., 2015; Tukker, 2013).

Three major benefits of CE model include economic, social, and environmental benefits. Economically, CE contributes to the high level of regional and domestic competitiveness through an increase in the effectiveness of resource allocation, resource utilization and productivity. This leads to greater economic stability as a result of resource security. In terms of environmental benefit, it reduces negative impacts on the environment by way of redesigning of the industrial structure in an ecological way. Socially, the CE model facilitates the creation of additional employment opportunities, equal distribution of economic growth and the improvement of well-being of people (Su et al., 2013; Morgan and Mitchell, 2015).

The activities of the construction industry have major impacts on the social, environmental and economic aspects of sustainability (Gencel et al., 2012). These activities have contributed to Gross Domestic Product (GDP), provided employment opportunities as well as other facilities to satisfy human beings' need (Smol et al., 2015). However, with the large amount of material intake, the construction industry generates large proportions of construction and demolition wastes yearly in the world (Clark et al., 2006). This waste generation has its attendant effect on the environment in the form of landfill depletion, carbon and greenhouse gas emission, huge wastage of embodied energy and raw materials and increased project costs (Faniran and Caban, 1998; Wang et al., 2014; Ekanayake and Ofori, 2004; Lieu et al., 2011). Considering the EU parliament's strategy for zero waste in Europe through the adoption of the circular economy model (COM, 2014) and the UK government's BIM strategy of adopting collaborative 3D BIM by 2016 (Cabinet Office, 2012). Development of a BIM-based tool for estimating the salvage performance of buildings presents an unprecedented opportunity for end-of-life management of the buildings in a circular economy.

To ensure effective circular economy, it is important that a good percentage of building materials are recoverable for reuse and recycling (Pan et al., 2015; Tukker, 2013). This ensures that the use of raw materials and the disposal of waste to landfill is minimised. Although building material recycling is a common practice, a more value-driven use of materials is reuse. This is because recycling requires more energy usage than material reuse. Accordingly, this study identifies factors influencing the reusability and recyclability of building materials. The factors are summarised in Table 1.

2.1. Factors influencing reusability of building materials

The reusability of recoverable building materials is affected by factors such as environmental (Viitanen et al., 2010), design and construction as well as operation and management factors (Kibert, 2003). Specification of reusable building materials during building design and construction phase (Webster and Costello, 2005; Guy et al., 2006) is a major factor that determines the level of reusability of recoverable materials at the end-of-life of a building. Other factors that influence the reusability of recoverable materials include: use of bolt and nut joints instead of nails and gluing (Crowther 2005; Webster and Costello, 2005; Guy et al., 2006) and the use of prefabricated assemblies (Crowther 2005; Guy and Ciarimboli, 2008). Layering of building element according to anticipated life span (Brand, 1994) facilitates cost effective recovery and reuse of building materials. The use of finishes on building materials reduces the possibility of reusing such materials as recovered (Crowther, 2005; Guy et al., 2006; Tingley, 2012).

2.2. Factors influencing recyclability of building materials

All the factors that influence reusability of recoverable building materials also indirectly influence the recyclability of the materials. For instance, a reusable material may not be usable as recovered because of damage or worn out. However, it could be considered for recycling. For example, carpet that is used in a building for several years, then ripped out and installed carpet in a new building project would be considered reusable. However, carpet that is installed in a building, ripped out and re-manufactured into wall insulation would be considered recyclable. Similarly, a steel beam in a building that is recovered at the end of life of a building and used as a beam in a new building construction is an example of direct reuse. In the same vein, re-manufacturing of the same steel beam into an entirely different material as result of damage to the original steel beam is an example of recycling. Specification of recyclable materials (Webster and Costello, 2005; Guy et al., 2006) is one of the factors that influence the recyclability of recoverable building materials. Another factor that connects to the specification factor is avoidance of the use of toxic and materials for the construction (Crowther 2005; Guy et al., 2006). The use of toxic and hazardous materials makes it impossible for the materials to recyclable at the end-of-life of the building. Layering of building element (Brand, 1994) also improve the efficiency of recycling as well as economic value of the recovered recyclable materials.

2.3. Building information modelling for circular economy

Building Information Modelling is an integrated process that involves collaboratively developing and using a computer generated parametric model of building to facilitate whole life management of building from planning to operation (Azhar et al., 2008; UNEP, 2016). Several works have been done to incorporate sustainability into BIM in the built environment. For example, a BIM-based design optimisation method for improving the sustainability of building is presented by Liu et al. (2015), where particle swarm optimisation technique was integrated with a BIM-based simulation system. Wu and Issa (2014) developed an Integrated Green BIM Process Map (IGBPM) for BIM execution in green building projects. Leadership in Energy and Environmental Design (LEED), a building sustainability rating system was used as a case study for IGBPM. The use of BIM within the Framework for Strategic Sustainable Development (FSSD) to facilitate bottom up strategies for cleaner production in the construction industry is becoming common practice (Alwan et al., 2017). Recently, the built environment has witnessed an increasing interest in the use of BIM in conjunction with sustainability principles during the design and construction of green building projects (Jalaei and Jrade, 2015).

One of the key features of BIM that makes it suitable for the circular economy process is its capability to accumulate lifecycle information about a building (Eadie et al., 2013). To ensure effective circular economy in the construction industry, the status and quality of the building materials in the economy must be known. To achieve this,

Table 1
Factors influencing reusability and recyclability of building materials.

No.	Factors	Reference	Material reusability	Material recyclability
1.	Specification of reusable materials during design	(Webster and Costello, 2005; Guy et al., 2006)	★	☐
2.	Specification of recyclable materials during design	(Webster and Costello, 2005; Guy et al., 2006)	☐	★
3.	Use of nut/bolt joints instead of nails and gluing	(Crowther, 2005; Webster and Costello, 2005; Guy et al., 2006)	★	☐
4.	Use of prefabricated assemblies	(Crowther, 2005; Guy and Ciarimboli, 2008)	★	☐
5.	Minimisation of types of building components	(Chini and Balachandran, 2002; Guy et al., 2006)	★	☐
6.	Avoidance of toxic and hazardous materials	(Crowther, 2005; Guy et al., 2006)	☐	★
7.	Layering of building element according to anticipated life span	Brand (1994)	★	★
8.	Avoidance of secondary finishes	(Crowther, 2005; Guy et al., 2006; Tingley, 2012)	★	☐

★ – key factors that must be considered. ☐ – factors that may be considered.

performance evaluation of building materials during and at the end-of-life is required. BIM therefore offers three core features that make it suitable for whole-life performance management of buildings (Bilal et al., 2016). These core features include: (i) object parametric modelling, (ii) bi-directional associativity and (iii) intelligent modelling.

Parametric modelling is a specialized way to capture design form and functionality using parameters and rules (Eastman et al., 2011; Zeng and Tan, 2006). Parametric representation ensures that the form and functionality of designs are preserved in response to contextual change (Bilal et al., 2016). Bi-directional associativity provides adequate support for changes that may occur in building models. This is because changes in one of the building elements may cause modifications to other elements. Examples of such scenarios include stretching of a wall, placing new components into a model, and changes in the material specification (Bilal et al., 2016). Intelligent modelling ensures that supplementary data are provided in addition to 3D geometric data. Relevant supplementary data include schedules, cost information, energy analysis details, lighting information, waste management plan, etc. These supplementary data are needed for various analytical, simulation and evaluation purposes.

3. Methodology

After a review of the literature on circular economy and BIM features, an objectivity-based methodology was adopted for this study. This approach requires a systemic operationalization of practices to drive genuine understanding of actions (Gray, 2009). Keeping with the foregoing, the development of BWPE follows the process of problem description, mathematical model formulation, obtaining of mathematical solutions to the model, simulation with the model and interpretation of the results as shown in Fig. 2. This approach is useful to characterise buildings and their salvage properties such that the mathematical model could assess the whole-life performance of the building by estimating its salvage performance based on design specifications and ageing. A case study approach was adopted to evaluate the performance of BWPE using comparative analysis of design typologies. Three scenarios of the case study building, which is a two-storey office building located in the South West of the UK were developed by specifying different materials for the structural component of the building. The ground floor area of the building is 491.49m^2. The floor plan of the case study building is shown in Fig. 3 and design characteristics features of the building are presented in Table 2.

Based on the design characteristic features shown in Table 2, three case studies were designed with three different major types of material, i.e., steel, timber and concrete. The essence of the comparative evaluation is to ascertain which of the building types has the potential for greater salvage value at the end of its useful life.

4. BWPE model development

The principle of reliability distribution of products underlies the proposed BWPE model. The most common probabilistic distribution functions often used to describe the reliability behaviour of products over their lifetime is the Weibull distribution function and its variance (Almalki and Yuan, 2013; Carrasco et al., 2008; Xie et al., 2002; Xie and Lai, 1996). In these functions, the reliability of a product is described by hazard function or failure rate. The hazard function is usually represented graphically using a bathtub shape as shown in Fig. 4 (Klutke et al., 2003; Xie and Lai, 1996). The bathtub curve explains the behaviour of products when put into operation. According to Xie and Lai (1996), the failure rate is high at the beginning of a product life cycle because of design and manufacturing errors and decreases toward a constant level during the useful part of the product life cycle. The product enters the wear-out phase after reaching a certain age and the failure rate starts to increase. A two-parameter variant of the Weibull distribution that is useful in modelling any of the three phases of the

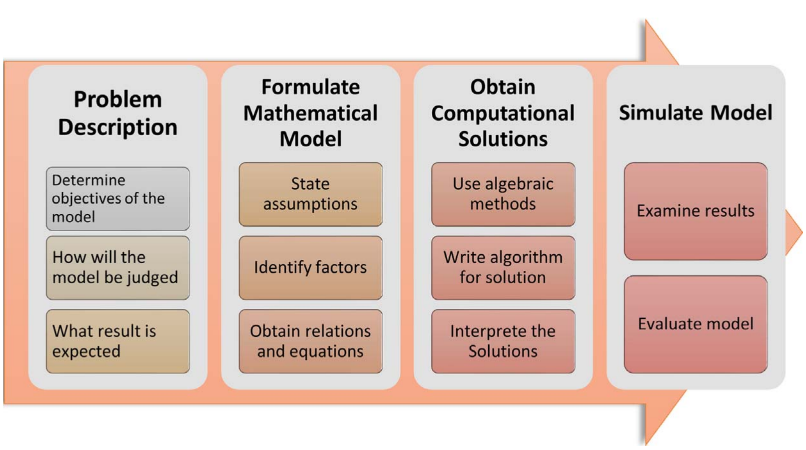

Fig. 2. Mathematical Modelling Process.

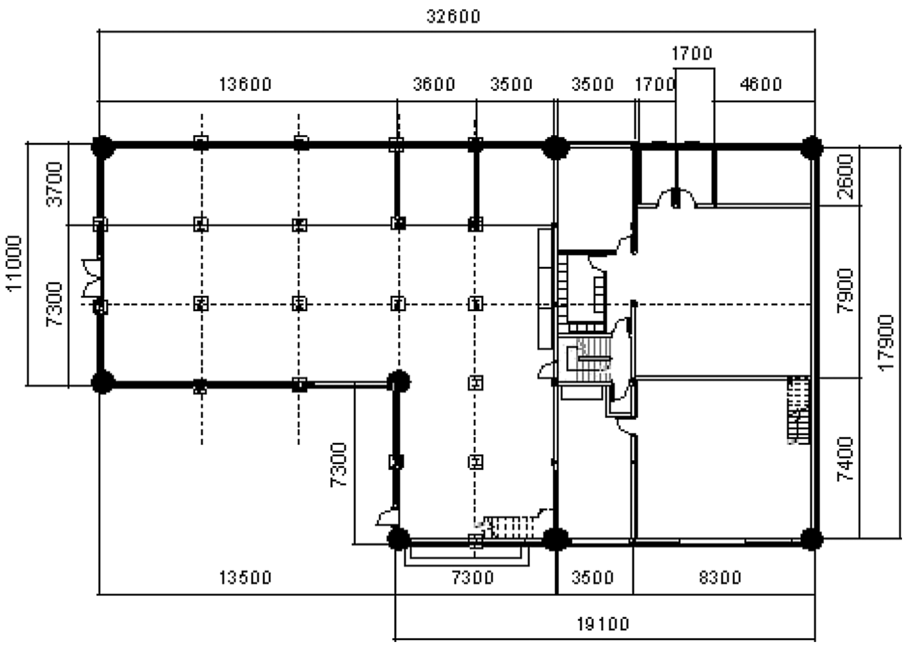

Fig. 3. Floor Plan of the Case Study Building.

Table 2
Characteristic Feature of the Case Study Building.

Feature	Value
Building type:	Office
Number of floors:	3
Ground floor area (GFA):	491.49 m^2
First floor GFA:	351 m^2
Second floor GFA:	351 m^2
Floor to ceiling height:	2.8 m
Second floor roof area:	402 m^2
Low level roof:	168 m^2

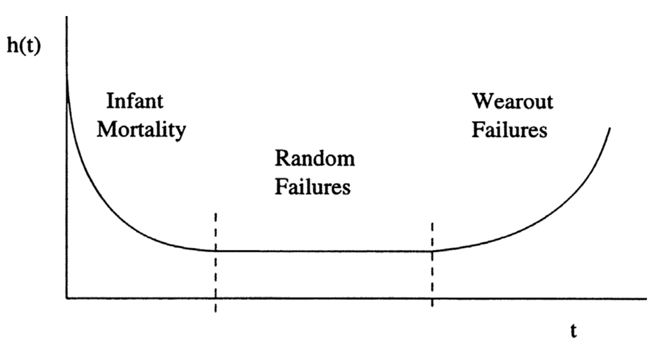

Fig. 4. Bathtub Curve – Hazard (Failure) function against time (Klutke et al., 2003).

bathtub curve is shown in Eq. (1). This equation and detail explanation of the parameters are presented in Xie and Lai (1996).

$$F(t) = 1 - \exp\left\{-\left(\frac{t}{\alpha}\right)^{\beta}\right\},\ t \geq 0 \tag{1}$$

where α is scale parameter, β is shape parameter and t is time.

In BWPE model development, the useful part of the product life cycle and the wear out period are considered. The infant mortality period is assumed not to affect the salvage performance of buildings. The useful period of the building life cycles is taken as the period from the day of building commissioning to the end of the buildings' life expectancy. The wear-out period is taken as the moments following the life expectancy period of buildings. A simplified form of the Weibull reliability equation is proposed for BWPE model. This approach became

Table 3
BWPE Model Parameters Description.

Notation	Description
S	Set of design specification, i.e., $S = \{S_1, S_2, \ldots, S_n\}$
$D(t)$	Deterioration function of the building, which is a function of time
t	Age of building in year
ndc	Number of demountable connections
nc	Total number of connections
d_c	Ratio of demountable connections to total connections
f_b	Ratio of prefabricated assemblies to total number of elements
nfb	number of prefabricated assemblies
ne	total number of possible building elements
$\bar{S}_f$	Ratio of volume of material without secondary finishes
$v\bar{S}_f$	Volume of materials without secondary finishes
vm	Total volume of building materials
$v\bar{h}_t t$	Volume of material without hazardous content
$\bar{h}_t$	Ratio of volume of materials without toxic content to the total volume of materials
SP	Salvage Performance of building $\{0 \leq SP \leq 1\}$
SP_{ru}	Reusable component of building
SP_{rc}	Recyclable component of building
γ	Fraction of building materials that goes to landfill
α	Life expectancy of building

necessary as there is no single reliability distribution function that can be used to model the behaviour of building materials without modification. Table 3 shows the variables and parameters used in the modelling and their meaning.

Given a BIM model of a building with well-defined design specification (S), then a building recoverability function denoted by Y for whole-life analysis is formally defined as a tuple comprising of S and deterioration factor $D(t)$:

$$Y = f\langle \mathrm{S,D(t)} \rangle \tag{2}$$

Where S is a set of the specified design features that influences the recoverability (reusability and recyclability) of building materials. $D(t)$ is the deterioration factor for the building over time.

The above functional definition is subject to the following constraints:

i) All instances of Y, i.e., $Y_i = \{Y|Y = (Y_1, Y_2. ..Y_n). D(t)\}$ estimate the salvage performance of the building at any time t. d

ii) A set of design specification S cannot be empty, i.e. $S \neq \phi$
iii) A set of design specification Smust be composed of tangible object and properties of all $S_i \varepsilon S$ must be identifiable and quantifiable: $\forall_{S_i \in S}$ [$\exists tangible(S_i)$](3)
iv) The deterioration function *D(t)* cannot be less than zero, i.e. $\forall_{x \in t}\, D(x) \geq 0$

Following the variables and parameters defined in Table 3 and the set of constraints mentioned above, the recoverability function Y is expanded as shown in equation 4 and the Salvage Performance (SP) of building is defined formally as presented from Eq. (5)

$$Y = S(S_1,\, S_2..S_n).\, D(t) \tag{4}$$

$$SP = Y + \gamma \tag{5}$$

Where Y is the building materials recoverability function and γ is the proportion of the building that goes to landfill. Therefore, substituting Equation 4 into equation 5 gives the expression (equation 6) for the salvage performance of building over time.

$$SP = [S(S_1,\, S_2..S_n).\, D(t)] + \gamma \tag{6}$$

The recoverability component of equation 6 instantaneously measures the reusability and recyclability of building materials. It is composed of design and construction factor part ($S(S_1,S_2..S_n)$) and ageing factor part ($D(t)$)

The details of how reusability and recoverability factors are obtained from the expression are presented in the following section.

From Eq. (6), it is important to maximise $S(S_1,\, S_2..S_n).\, D(t)$while minimising γ. This is to ensure that the optimal value is derived from the building at the end-of-life and to reduce the proportion of the building materials that goes to the waste stream. Keeping with the foregoing, a set of points between the beginning and the end-of-life of a building for which the function $S(S_1,\, S_2..S_n).\, D(t)$attains the highest recoverability value could be computed. This is done by computing the argument of the maxima (argmax), which determines the point within the domain at which the function is maximised. Therefore, given a subset of time $T = [0, \alpha]$, the argmax over t is shown in Eq. (7).

$$\underset{t \in T}{\operatorname{argmax}}\, f(t) = \{t | t \in T \wedge \forall\, w{:}\, f(w) \leq f(t)\} \tag{7}$$

This function is useful to determine the best time at which the optimal value could be derived from a building when it gets to its end-of-life. Although, it is not economically wise to deconstruct or demolish a building during its useful life for reuse or recycle. It is important to identify recoverable elements and measure their potential salvage performance. This will in turn provide support for the secondary material market in a circular economy.

4.1. Salvage performance model of building materials

The salvage performance of buildings is dependent on two group of factors namely: design and construction factors and ageing factor. Four quantifiable factors are selected from the list of identified factors that influence reusability and recyclability of building materials earlier presented in Table 1. The factors are (i) use of demountable connections (d_c), (ii) use of prefabricated assemblies (f_b), (iii) avoidance of materials with secondary finishes ($\overline{S}_f$) and (iv) ($\overline{h}_t$)use of materials with no toxic or hazardous content

Accordingly, we establish the relationship function for design factor component of equation 6 by aggregating the effect of the selected factors on the recoverability of the building materials. In general term,

$$S(S_1,S_2.S_n)\ \alpha\ f\ (S_1,S_2,S_3..Sn) \tag{8}$$

Where n is the number of factors being considered. The expression in equation 8 generates reusability and recyclability factors that complement each other. For example, a design specification may fully support

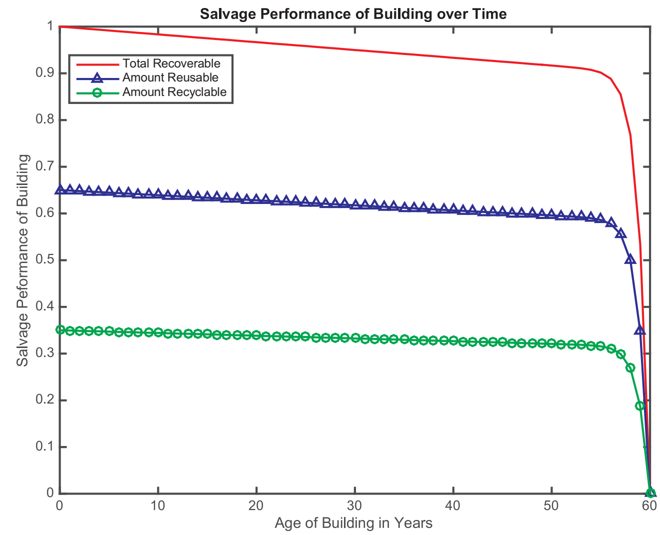

Fig. 5. Salvage Performance of Building.

reusability or recyclability whereas another design specification may partly support either reusability or recyclability. An expression for reusability S_{ru} based on Eq. (8) with $S_1 = d_c$, $S_2 = f_b$, $S_3 = \overline{S}_f$ and $S_4 = \overline{h}_t$, is presented in Eq. (9). This is the expression for the design and construction component of Eq. (6).

$$S_{ru} = (\beta d_c + \lambda f_b + \mu \overline{S}_f + \rho \overline{h}_t) \tag{9}$$

where parameters β, λ, μ and ρare the weighting function that determines the significance of each of the factors to the reusability of building materials at the end-of-life. In this study, the same level of significance of 0.25 is used for each of the four factors. Although an assumption of the same level of significance for all the factors in determining salvage performance of building may seem impracticable, it however, provides a grip on the achievement of the objectives of the current study.

To obtain the effect of the four factors on the reusability of the building components, the demountable connection d_c is taken as a fraction of the total number of connections in the building that are demountable as shown in Eq. (10).

$$d_c = \frac{ndc}{nc} \tag{10}$$

where *ndc* is the number of demountable connections specified in a design and *nc* is the total number of connections in a building. In the same way, the use of the prefabricated assembles (f_b) is the ratio of the number of prefabricated assemblies used to the total number of building elements. This is represented in Eq. (11).

$$f_b = \frac{nfb}{ne} \tag{11}$$

From Eq. (11), *nfb* is the number of the prefabricated assemblies, *ne* is the total number of building elements. The expressions for obtaining $\overline{S}_f$ and $\overline{h}_t$ are given in Eq. (12) and (13). Eq. (12) is the ratio of the volume of the materials without secondary finishes to the total volume of materials used for the building. The ratio of the volume of materials without hazardous and toxic materials to the total volume of building materials is presented in equation 13.

$$\overline{S}_f = \frac{v\overline{S}f}{vm} \tag{12}$$

$$\overline{h}_t = \frac{v\overline{h}t}{vm} \tag{13}$$

Therefore, the expression for the reusability component S_{ru} of the equation 9 is obtained by substituting Eqs. (10), (11), (12), and (13)

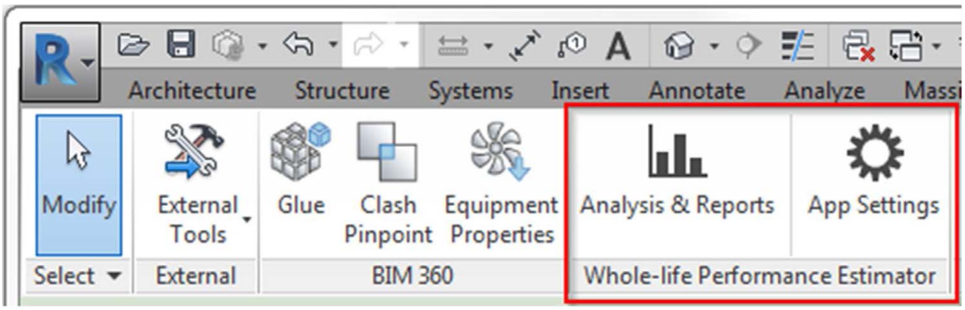

Fig. 6. Implementation of BWPE functionality in BIM Environment.

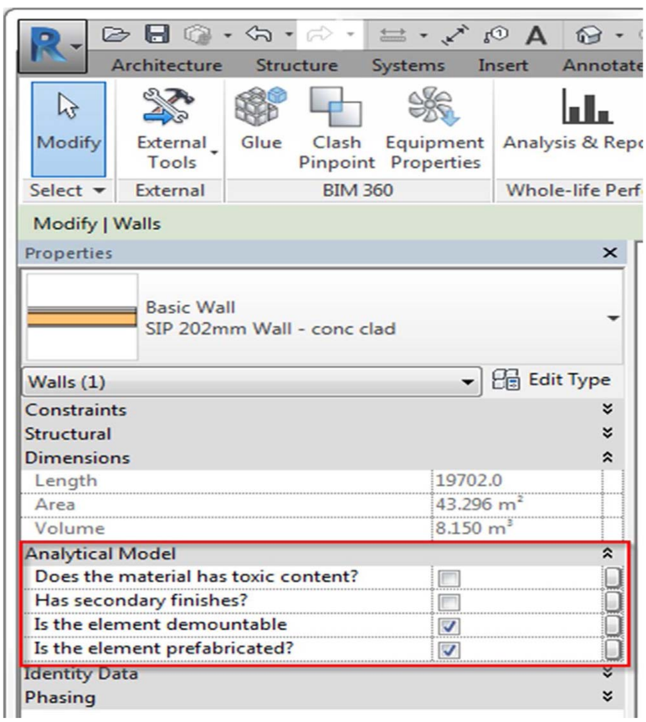

Fig. 7. Custom Parameter Creation Interface in Revit.

into equation (9) as shown in Eq. (14).

$$S_{ru} = \left(\beta\frac{ndc}{nc} + \lambda\frac{nfb}{ne} + \mu\frac{v\bar{S}f}{vm} + \rho\frac{v\bar{h}t}{vm}\right) \tag{14}$$

Conversely, the effect of the four factors on the recyclability of the building component is the compliment of that of reusability. This is shown in Eq. (15).

$$S_{rc} = 1 - S_{ru} \tag{15}$$

Eqs. (14) and (15) provide the fraction of a building that is reusable and recyclable respectively at any time during the life cycle of the building.

The deterioration factor $D(t)$ of equation 6 is used to capture the effect of the passage of time on the building. It is modelled as a reliability function. The use of reliability function (or failure rate) as a measure of performance of products is well established in the literature (Almalki and Yuan, 2013; Carrasco et al., 2008; Xie et al., 2002). Therefore, the deterioration function of the salvage performance of buildings is modelled with the use of an exponential distribution, which is an adaptation of the Weibull distribution (Eq. (1)). This is shown in Eq. (16).

$$\mathrm{D}(t) = 1 - e^{t-\alpha} - \varepsilon \tag{16}$$

Where t is the age of the building, α is the life expectancy of the building. For example, the life expectancy of a building is put at 60 years in the UK (BSI, 2015; Lawson, 2016), ε is the degradation factor that accounts for initial gradual degradation of the building. A typical value for ε is shown in equation 17. Although the life expectancy of 60 years has been used to simulate the effect of the passage of time on building structure, this value could be replaced with the actual age of the building that has reached the end of its useful life.

$$\varepsilon = \frac{t}{10 * \alpha} \tag{17}$$

Substituting the expression for ε in Eq. (17) into Eq. (16) gives the expression for the ageing factor component of Eq. (6). This is presented in Eq. (18).

$$\mathrm{D}(t) = 1 - e^{t-\alpha} - \frac{t}{10 * \alpha} \tag{18}$$

From the expressions derived above, the salvage performance equation provides estimation for the reusable and recyclable components of building at any point in time. Therefore, applying the expression for deterioration factor shown in equation 18 to the expression for reusability component of design factors (equation14) gives the final expression for the reusability component of the salvage performance equation as shown in equation 19. Accordingly, the expression for the recyclability component of salvage performance expression (i.e. $1 - SP_{ru}$) is presented in Eq. (20). It is important to note that in a circular economy, the aim is to maximise the reusability of building materials.

$$SP_{ru} = \left(\beta\frac{ndc}{nc} + \lambda\frac{nfb}{ne} + \mu\frac{v\bar{S}f}{vm} + \rho\frac{v\bar{h}t}{vm}\right)\left(1 - e^{t-\alpha} - \frac{t}{10 * \alpha}\right) \tag{19}$$

$$SP_{rc} = \left(1 - \left(\beta\frac{ndc}{nc} + \lambda\frac{nfb}{ne} + \mu\frac{v\bar{S}f}{vm} + \rho\frac{v\bar{h}t}{vm}\right)\right)\left(1 - e^{t-\alpha} - \frac{t}{10 * \alpha}\right) \tag{20}$$

Therefore, the overall salvage performance of building (Eq. (6)) becomes;

$$SP = SP_{ru} + SP_{rc} + \gamma \tag{21}$$

where SP_{ru} is the estimate of the recoverable materials from a building that are reusable and SP_{rc} is the estimate of the recoverable materials from a building that are recyclable (i.e. not reusable without further processing), and γ is the amount of the building materials that enter the waste stream because of ageing.

4.2. Model simulation

To visualise and test the functioning of the mathematical model formulated above for estimating the salvage performance of buildings over time, it is necessary to simulate the model with a typical data set. The simulation experiment was run in Matlab environment for a building design with various S_{ru} and S_{rc} values. Fig. 5 shows the salvage performance behaviour of a building with $S_{ru} = 0.65$ and $S_{rc} = 0.35$. From the figure, the red line curve shows the fraction of the materials

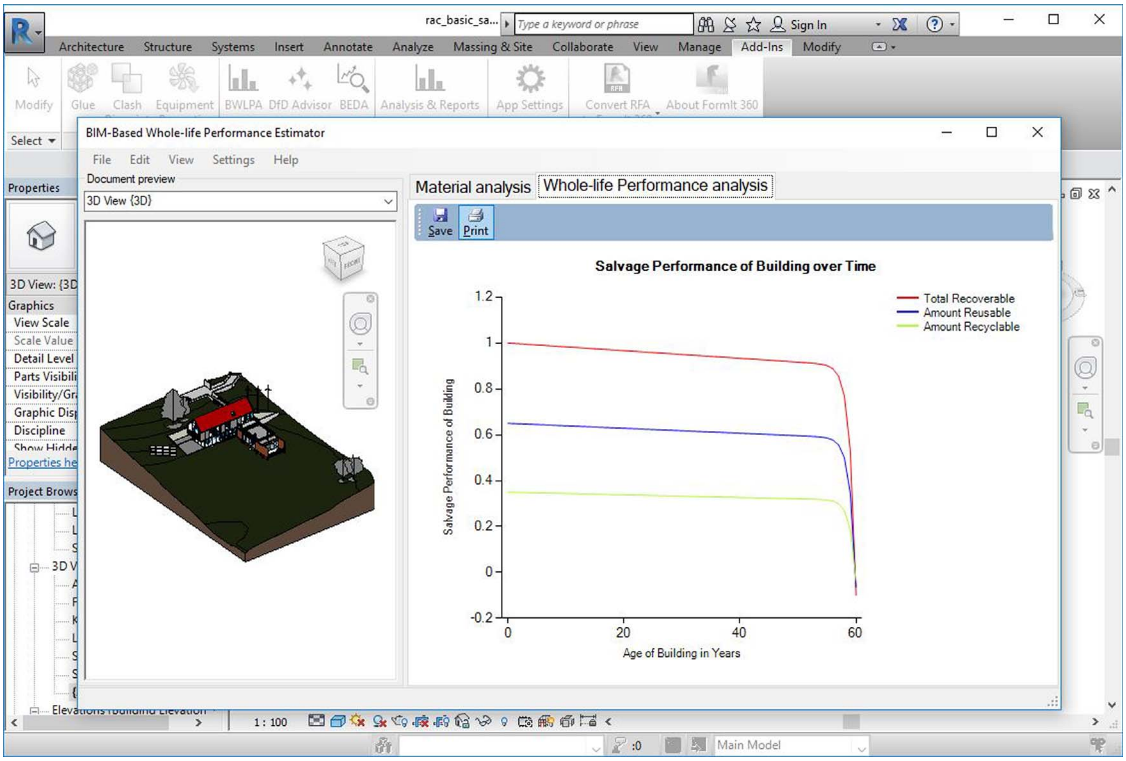

Fig. 8. Sample Result of Whole-Life Performance Analysis of a BIM Model.

that are recoverable from building's take-off material over time. The amount of recoverable materials from the building decrease slightly and steadily over the life span of the building, however, as the building approaches its end of life, a sharp decrease in the amount is noticed. This is in line with the behaviour of materials generally as earlier demonstrated with bathtub curve for the failure rate. The figure shows that as buildings approache their end of life (60 years in this case), the materials in the building enter the wear out phase and their recoverability degrades drastically. The line with blue triangles represents the amount of the recoverable materials that are reusable while the line with green circles depicts the amount of the recoverable materials that are recyclable.

4.3. Model integration with BIM

One of the three core features that make BIM suitable for whole-life assessment of building is the Intelligent modelling (Bilal et al., 2016). This feature allows additional information to be provided and integrated to the 3D geometric data. Accordingly, the functionality provided by BWPE was implemented in BIM environment in the form of an add-in Autodesk Revit as shown in Fig. 6. Revit Application Programming Interface (API), Visual Studio and C# programming language were used to realise the integration of the BWPE functionality with the Revit software.

Custom parameters (such as identification of demountable connection, use of prefabricated assembles etc.) required by BWPE for its functioning were created as shown in Fig. 7. To run the whole-life performance assessment on a building model, the parameters must be properly specified for each component of the building under the “App Setting” tab of the interface. A typical result of the analysis of the case study building design is shown in Fig. 8.

5. Model evaluation

BWPE model developed was evaluated on the case study building with three major structural components. The three design specifications are steel structure, timber structure and concrete structure. Various possible design and material selection options for the three types of the building structures are as shown in the material selection option look-up table (Table 4). Based on the options available in the table, the design and materials properties of the three case studies are presented in Table 5. The volume of the building materials for the design types was obtained from the bill of quantity of the material take-off specified in the BIM model of the building within Revit software environment. Possible design specification parameters (shown in Table 4) are specified in the shared parameter feature of the Revit software. For the evaluation, the design parameter for the three scenarios of the case study building were selected based on the available option in the material selection look-up table. Accordingly, different design options was selected for the three scenarios of the case study.

The result of the evaluation is presented in Table 6. The table shows the result of the effect of design and construction factors on the salvage performance of the buildings. Figs. 9–11 show the overall salvage performance of the case study when the structural component of the building is largely made up of steel, timber and concrete respectively. The effect of ageing on the salvage performance of the buildings is reflected in the recoverability curves of the three graphs (i.e. the curve in red colour line). The amount of the recoverable materials that are reusable and recyclable are respectively depicted with the curve in blue triangles and curve in green circles. From the figures, the building with the structural components largely made of steel has 0.93 reusability and 0.07 recyclability, while the building with timber structure has 0.65 reusability and 0.35 recyclability. The building with concrete structure has 0.42 reusability and 0.58 recyclability. From the results, the building with steel structure has the highest reusability ratio. This is because of the use of mostly demountable connections and prefabricated assemblies. Although timber based structures are mostly reusable, it has a reusability ratio of 0.65 in this case. This is due to the use of nail for most of the connections in the building. The concrete has the least reusability of 0.42, this is usually the case with the concrete structure, they are generally difficult and inflexible to reuse (Davison and Tingley, 2011). They are however readily recyclable.

Table 4
Materials selection options for building system.

Systems and options	Recyclable (r_1)	Reusable (r_2)	Toxic (x)	Sec. Finish (s)	Connection type
1. Structural Foundations					
H-Pile foundation	✓	✓	×	×	c_b
Concrete ground beam	✓	×	×	×	c_f
Concrete with mastic tanking	✓	×	×	×	c_f
2. Floor system					
Insitu Concrete floor with ceramic tiles	✓	×	×	×	c_f
Precast Concrete slab with carpet	✓	×	×	×	c_d
Timber floor with ceramic tiles	✓	✓	×	×	c_n
3. Structural frame system					
Exposed Steel with fixed connections					
Concrete Encased Steel with fixed connections	✓	✓	×	×	c_f
Exposed Steel with bolted connections	✓	×	×	×	c_f
Concrete Encased Steel with bolted connections	✓	✓	×	×	c_b
Timber with bolted connections	✓	✓	×	×	c_d
Timber with nailed connections	✓	×	×	×	c_b
Reinforced Concrete with bolted connections	✓	✓	×	✓	c_f
4. Wall system					
Demountable dry internal wall – Steel					
Curtain wall	✓	✓	✓	✓	c_b
Brick/block cavity wall	✓	✓	×	×	c_b
Cladded timber cavity wall	✓	×	×	✓	c_b
Steel framed wall	✓	×	×	✓	c_n
5. Doors and windows					
Glass with aluminium frame					
Timber with timber frame – Softwood	✓	✓	×	×	c_b
Timber with timber frame – Hardwood	✓	✓	×	✓	c_n
6. Ceiling system					
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_n
7. Roof system					
Flat galvanised steel on Z profile beams	✓	✓	×	×	c_n
Reinforced concrete roof with sand/cement screed	✓	✓	×	×	c_n
Pitched roof timber structure	✓	×	×	✓	c_f
Tiles covering on pitched roof	✓	✓	×	×	c_n

It should be noted that the BWPE tool presents an opportunity for building designers to try different combinations of the factors and examine the effect on the salvage performance of buildings. This will be especially useful in determining the degree of building material circularity that a building will support when it gets to its end-of-life. Accordingly, the tool provides a means of evaluating possible sustainability options for a building at the design stage. Possible specification option includes steel structure with fixed connection and secondary finishes, concrete structure with most component prefabricated and no secondary finishes, timber structure with no secondary finishes and mostly demountable connection etc. Although the design specification is a function of other factors that are beyond the scope of this study, the model will certainly provide support for the designer in understanding the end-of-life effect of the design decision being taken.

6. Discussion

The mathematical model presented in this work is a tool that could be used at the design stage to estimate the amount of material that could be recovered from a building at any time during the building's whole life period. The model also provides insights into the amount of the recoverable material that could be reusable and the amount that could be recyclable. The recoverability curves in Figs. 9–11 show a gradual and steady decrease in the amount of recoverable materials throughout the entire life cycle of the building, the rate of degradation however increased sharply as the building approaches the end of its life. The reusability and recyclability curves are the reflection of design and materials specification in the building model.

The primary goal of a circular economy is to use and reuse materials, BWPE model provides an opportunity for building designers to simulate the whole life performance of buildings and make necessary adjustments to the design thereby leading to buildings with efficient materials recovery for the circular economy. The results from the case studies show that buildings with steel structure and demountable connections provide recoverable materials that are mostly reusable. Whereas buildings with concrete structure generate recoverable materials that are mostly recyclable. The recoverable materials from building with timber structure are 65% reusable and 35% recyclable. This performance can be improved with the use of demountable connections, i.e. dowels and bolt and nut instead of nails for most connections.

Although the costs of buildings with steel structures and demountable connections are high, the costs are paid back by perpetually keeping the materials from the building in the circular economy. This thus preserves the embodied energy of the materials and prevent generation of waste to landfill thereby reducing carbon footprint of the material on the environment. The use of prefabricated assemblies in buildings also contributes greatly to the reduction of construction and demolition wastes (Baldwin et al., 2008; Tam et al., 2005; Lu and Yuan, 2013). Recently, Alireza et al. (2017) presented a framework for sustainability assessment of building materials supply decisions. Integrating BWPE into the framework will provide a robust system for sustainability assessment of building design options and materials selection.

Table 5
Design Specification of the Case Study Building.

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

BWPE is a BIM-based system that could be used by all the practitioners in the construction industry, leveraging on the capabilities of BIM such as parametric modelling, visualisation, material database, etc. to analyse and visualise the effects of design decisions and materials selection on salvage performance of buildings. BWPE is expected to be used by the practitioners in the construction industry to estimate the salvage performance of buildings. The tool will also be useful in the demolition industry by providing a support tool for generating pre-demolition audit for buildings that are to be demolished.

Although, some works have been done to enable BIM for sustainability assessment of building designs (Liu et al., 2015; Jalaei and Jrade, 2015; Alwan et al., 2017). The dimensions of sustainability covered by these works are limited to economic and environmental sustainability. The assessment of the social aspect of sustainability has been reported to be lacking in most modern tools and systems for building sustainability assessment (Ahmad and Thaheem, 2017; Alireza et al., 2017). Therefore, future development of BWPE will be in the development of BIM-based capacity for evaluating the social aspect of sustainability of buildings from the design stage. This will provide BIM with the capability to evaluate building designs for the three dimensions of sustainability (i.e. economic, environmental and social).

7. Conclusion

This study presents the mathematical modelling of a BIM-based building salvage performance estimator. The model was based on factors that influence recoverability of materials and reliability distribution of building materials. The model was evaluated using three design specifications of a real-life building case study. The results of the evaluation show that building design with steel structure, demountable connections and prefabricated assemblies generate recoverable materials that are mostly reusable (i.e. 93% reusable, 07% recyclable). Whereas, building design with concrete structure generates recoverable materials that are mostly recyclable. The design with timber structure generates recoverable materials that are largely reusable (i.e. 65% reusable, 35% recyclable). The implication of the reusability and recyclability values of the case studies is that, for a steel based structure for instance, 97% of the recoverable materials will be reusable for the same or similar function and 7% of the materials will be required to undergo some processing before they could be useful. However, part of the 93% reusable could also be subjected to recycling to meet another functional requirement.

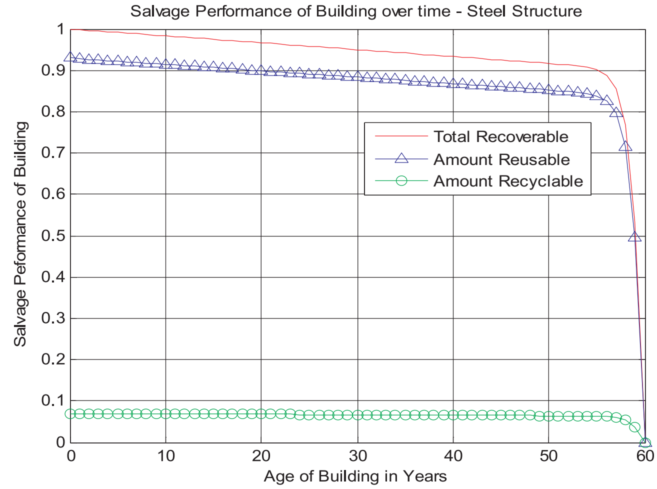

Fig. 9. Salvage Performance of Case Study Building – Steel Structure.

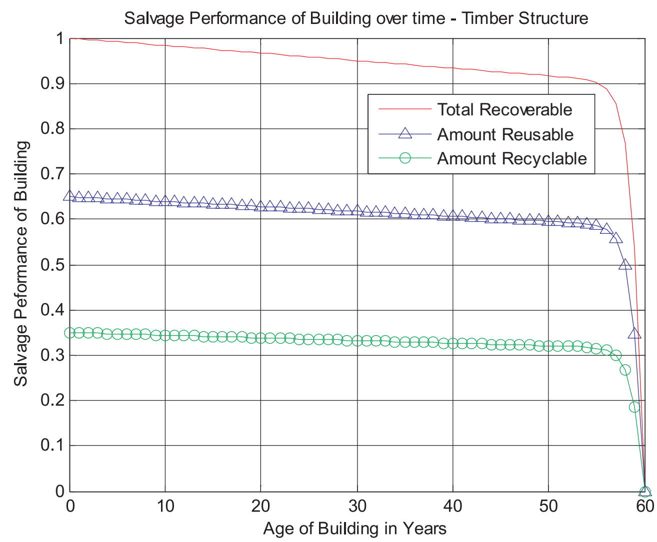

Fig. 10. Salvage Performance of Case Study Building – Timber Structure.

The contributions of this study therefore include: (i) creation of a

Table 6
Result of Model Evaluation of the Case Study Buildings.

Case Study	nc	ndc	ne	nfb	vm	$v\bar{S}f$	$v\bar{h}t$	S_{ru}	S_{rc}
Steel	256.00	206.00	64.00	64.00	10000.00	9000.00	10000.00	0.93	0.07
Timber	256.00	20.00	64.00	40.00	10000.00	9000.00	10000.00	0.65	0.35
Concrete	256.00	20.00	64.00	0.00	10000.00	8000.00	8000.00	0.42	0.58

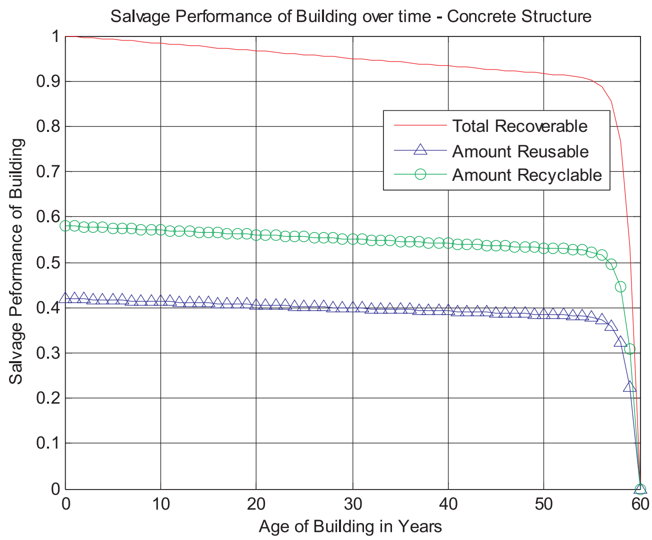

Fig. 11. Salvage Performance of Case Study Building – Concrete Structure.

BIM-based tool for estimating the salvage performance of buildings from the design stage. This is the first of its kind in the UK construction industry. (ii) provision of an objective assessment method for evaluating buildings' potential for compliance with the circular economy goal. This helps to preserve the embodied energy of building material and reduce waste generation to landfill. This study has huge implications for both academic and industry practice. For academics, the study brings to the fore, factors that must be considered when designing buildings that requires high end-of-life performance. It also improves the understanding of how the prediction of salvage could be formulated into a computational system. For the industry, since BIM adoption is required to sustain competitive advantage in the changing AEC industry. As such, this study integrates salvage performance analysis into BIM platform to support architects and building designers. The availability of a tool like BWPE within BIM environment will improve its acceptability and usability among industry practitioners. In addition, adopting a BIM approach to end-of-life salvage performance analysis will allow easy exchange of data between BWPE and existing BIM analysis tools. As such, salvage performance at design stage provides a mechanism for supporting lifetime management and end-of-life decisions. This will enable end-of-life performance to be simulated vis-à-vis other building performance requirements.

Despite the contributions of this study, there are certain limitations. First, different building components have different life expectancy and react differently to different environmental conditions. Estimating salvage performance of a complete building system is complex and depends on factors that may be difficult to objectively quantify. Even so, developing a holistic performance estimator for different group of these components is cumbersome and may not be practicable. For, example, paint and finishes may last for about 2 years while Heating Ventilation and Air Conditioning (HVAC) systems could last up to 15 years. Whereas glazing and facade units and building structure can easily reach 25–30 years and 75–100 years respectively. This leads to a high complexity in lifetime and status prediction of the component groups. BWPE estimates the overall salvage performance at the building level. It is noted during this work that estimating the salvage performance of individual materials that make up building elements requires more complex analysis, which is not considered in this work.

In addition, the modelling approach and Weibull distribution adopted in this study are relevant for general life expectancy prediction, but setting this up for a specific material group is not trivial. Therefore, this work is limited to the materials analysis of the structural component of buildings under normal operational usage. These structural components are foundations, columns, beams, upper floors, walls and stairs. Although the lifetime of building components largely depends on building usage (occupancy, activities, behaviour), it is difficult to objectively measure this metric. As such, this study did not consider building usage as part of the parameters for building salvage performance estimation. Further works are therefore suggested to consider the possibility of estimating the salvage behaviour of buildings by considering all building components and building usage.

Acknowledgments

The authors would like to acknowledge and express their sincere gratitude to the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK (grant applications No. 54832-413479/File No. 102473) for providing the financial support for this study.

References

Addis, B., 2006. Building with Reclaimed Components and Materials: A Design Hand Book for Reuse and Recycling. Earthscan, London.

Ahmad, T., Thaheem, M.J., 2017. Developing a residential building-related social sustainability assessment framework and its implications for BIM. Sustain. Cities Soc. 28, 1–15.

Akinade, O.O., Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A., Bello, S.A., 2015. Waste minimisation through deconstruction: a BIM based deconstructability assessment score (BIM-DAS). Resour. Conserv. Recycl. 105, 167–176. http://dx.doi.org/10.1016/j.resconrec.2015.10.018.

Alireza, A.F.F., Taha, H.R., Waller, S.T., 2017. BIM-enabled sustainability assessment of material supply decisions. Eng. Constr. Archit. Manage. Vol. 24 (is. 4), Pp. 668–695. http://dx.doi.org/10.1108/ECAM-12-2015-0193.

Almalki, S.J., Yuan, J., 2013. A new modified Weibull distribution. Reliab. Eng. Syst. Saf. 111, 164–170. http://dx.doi.org/10.1016/j.ress.2012.10.018.

Alwan, Z., Jones, P., Holgate, P., 2017. Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using building information modelling. J. Clean. Prod. 140, 349–358.

Andersen, M.S., 2007. An introductory note on the environmental economics of the circular economy. Sustain. Sci. 2, 133–140.

Azhar, S., Nadeem, A., Mok, J.Y., Leung, B.H., 2008. In: Building Information Modeling (BIM): A New Paradigm for Visual Interactive Modeling and Simulation for Construction Projects. August 4–5. pp. 435–446.

BCIS, 2006. Life Expectancy of Building Components: Surveyor's Experiences of Building in Use A Practical Guide. Connelly-Manton (Printing) Ltd., London.

BRE, 2017. Integrated Material Profile And Costing Tool. Bruilding Research Establishment. [Retrieved 2017 July 2014] Available at: http://www.bre.co.uk/page.jsp?id=2181.

BSI, 2015. – Guide to Durability of Buildings and Building Elements, Products and Components. British Standard Institute Limited.

Baldwin, A.N., Shen, L.Y., Poon, C.S., Austin, S.A., Wong, I., 2008. Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings. Autom. Constr. 17 (3), 333–341.

Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., Akinade, O.O., Ajayi, S.O., Owolabi, H.A., 2016. Analysis of critical features and evaluation of BIM software: towards a plug-in for construction waste minimization using big data. Int. J. Sustain. Build. Technol. Urban Dev. 7628 (January). http://dx.doi.org/10.1080/2093761X.2015.1116415.

Brand, S., 1994. How buildings learn: what happens after they are built. Viking, New York.

Brundtland, G.H., 1987. Our common future: report of the world commission on environment and development. Med. Conflict Surviv. 4 (1), 300. http://dx.doi.org/10.1080/07488008808408783.

COM, 2016. Commission of European Communities. Communication No. 398, 2014. Towards a Circular Economy: A Zero Waste Programme for Europe. [Retrieved 30 October 2016] Available at: http://europeanmemoranda.cabinetoffice.gov.uk/files/2014/07/11592-141.pdf.

Government Construction Strategy. . [Retrieved 2016 November 2001] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61151/GCS-One-Year-On-Report-and-Action-Plan-Update-FINAL_0.pdf.https://doi.org/Vol19.

Carrasco, J.M.F., Ortega, E.M.M., Cordeiro, G.M., 2008. A generalized modified Weibull distribution for lifetime modeling. Comput. Stat. Data Anal. 53 (2), 450–462. http://dx.doi.org/10.1016/j.csda.2008.08.023.

Chini, A.R., Balachandran, S., 2002. Anticipating and responding to deconstruction through building design. Proceedings of Design for Deconstruction and Materials Reuse CIB Publication 272, 175–185.

Chong, H.-Y., Lee, C.-Y., Wang, X., 2017. A mixed review of the adoption of Building Information Modelling (BIM) for sustainability. J. Clean. Prod. 142, 4114–4126.

Clark, C., Jambeck, J., Townsend, T., 2006. A review of construction and demolition debris regulations in the United States, critical reviews in. Environ. Sci. Technol. 36 (2), 141–186. http://dx.doi.org/10.1080/10643380500531197.

Coates, P., Arayici, Y., Koskela, K., Kagioglou, M., Usher, C., O'Reilly, K., 2013. The key performance indicators of the BIM implementation process. In: The International Conference on Computing in Civil and Building Engineering. June 30 – July 2.

Coelho, A., de Brito, J., 2011. Economic analysis of conventional versus selective demolition – a case study. Resour. Conserv. Recycl. 55, 382–392.
Crowther, P., 2005. Design for Disassembly – Themes and Principles. RAIA/BDP Environment Design Guide. Available at: https://doi.org/10.1115/1.2991134. [Retrieved 2016 Nov 20].
DEFRA, 2015. Department for Environment, Food and Rural Affairs ? UK Statistics on Waste. [Retrieved 16 November 2016]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/487916/UK_Statistics_on_Waste_statistical_notice_15_12_2015_update_f2.pdf (Accessed 28 Feburary 2016).
Davison, B., Tingley, D.D., 2011. Design for Deconstruction and Material Reuse Proceeding of the ICE – Energy 164 (4), 195–204.
Douglas, I., 2016. The circular economy Waste. J. Commonw. Human Ecol. Counc London.
Eadie, R., Browne, M., Odeyinka, H., McKeown, C., McNiff, S., 2013. BIM implementation throughout the UK construction project lifecycle: an analysis. Autom. Constr. Vol. 36, 145–151.
Eastman, C., Teicholz, P., Sacks, R., Liston, K., 2011. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. John Wiley & Sons Hoboken, New Jersey.
Ekanayake, L.L., Ofori, G., 2004. Building waste assessment score: design-based tool. Build. Environ. 39 (7), 851–861.
Falk, B., 2002. Wood-framed building deconstruction: a source of lumber for construction? For. Prod. J. 52 (3), 8–15.
Faniran, O.O., Caban, G., 1998. Minimizing waste on construction project sites engineering. Constr. Archit. Manage. 5 (2), 182–188.
Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768.
Gencel, O., Ozel, C., Koksal, F., Erdogmus, E., Martínez-Barrera, G., Brostow, W., 2012. Properties of concrete paving blocks made with waste marble. J. Clean. Prod. 21 (1), 62–70.
Gray, D.E., 2009. Doing Research in the Real World Sage. Publications Ltd., London.
Guy, B., Ciarimboli, N., 2008. DfD: Design for Disassembly in the Built Environment: a Guide to Closed-loop Design and Building. Hamer Center.
Guy, B., Shell, S., Esherick, H., 2006. Design for deconstruction and materials reuse. Proceeding of CIB Task Group 39 189–209.
Hyder Consulting, 2011. Construction and Demolition Waste Status Report ? Management of Construction and Demolition Waste in Australia. A Report Prepared for the Department of Sustainability, Environment, Water Population and Communities Queensland.
IMPACT, 2017. How to Get IMPACT Whole Building Assessment Tools. [Retrieved 14 July. 2017] Available at: http://www.impactwba.com/page.jsp?id = 1.
Kibert, C.J., Chini, A.R., Languell, J., 2001. Deconstruction as an Essential Component of Sustainable Construction. CIB World Congress, Wellington, New Zealand. Available from http://www.irbnet.de/daten/iconda/CIB3122pdf.
Kibert, C.J., 2003. Deconstruction: the start of a sustainable materials strategy for the built environment. Ind. Environ. 26 (2–3), 84–88.
Kibert, C.J., 2008. Sustainable Construction: Green Building Design and Delivery: Green Building Design and Delivery. John Wiley & Sons.
Klutke, G.A., Kiessler, P.C., Wortman, M.A.1, 2003. A critical look at the bathtub curve. IEEE Trans. Reliab. 52 (1), 125–129. http://dx.doi.org/10.1109/TR.2002.804492.
Lawson, N., 2016. Construction and demolition: resources usage and recycling. In waste. J. Commonw. Human Ecol. Counc London.
Lieu, Z., Osmani, M., Demain, P., Baldwin, A., 2011. The Potential use of BIM to aid construction waste minimization. In: Proceedings of the CIB W78-W102 2011. INTERNATIONAL Conference (26–28 October, pp. 1–13), Sophia Antipolis, France.
Liu, S., Meng, Z., Tam, C., 2015. Building information modeling based building design optimization for sustainability. Energy Build. 105, 139–153.
Lu, W., Yuan, H.1, 2013. Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. Renew. Sustain. Energy Rev. 28, 804–811.
Morgan, J., Mitchell, P., 2015. Employment and the Circular Economy – Job Creation in a More Resource Efficient Britain. Green Alliance. [Retrieved 13 July 2013] Available at: http://www.wrap.org.uk/sites/files/wrap/Employment%20and%20the%20circular%20economy%20summary.pdf.
Nakajima, N., 2000. A vision of industrial ecology: state-of-the-art practices for a circular and service-based economy. Bull. Sci. Technol. Soc., vol. 20, 54–69.
Pan, S.-Y., Alex Du, M., Liu, I., Liu, I., Chang, E., Chiang, P., 2015. Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. J. Clean. Prod. 108, 409–421.
Rashid, A., Asif, F.M.A., Krajnik, P., Nicolescu, C.M., 2013. Resource conservative manufacturing: an essential change in business and technology paradigm for sustainable manufacturing. J. Clean. Prod. 57, 166–177.
Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., Wzorek, Z., 2015. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. J. Clean. Prod. 95, 45–54. http://dx.doi.org/10.1016/j.jclepro.201 5.02.051.
Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227. http://dx.doi.org/10.1016/j.jclepro.2012.11.020.
Succar, B., Kassem, M., 2015. Macro-BIM adoption: conceptual structures. Autom. Constr. 57, 64–79.
Tam, C.M., Tam, V.W.Y., Chan, J.K.W., Ng, W.C.Y., 2005. Use of prefabrication to minimize construction waste-a case study approach. Int. J. Constr. Manage. 5 (1), 91–101.
Thormark, C., 2006. The effect of material choice on the total energy need and recycling potential of a building. Build. Environ. 41 (8), 1019–1026. http://dx.doi.org/10.1016/j.buildenv.2005.04.026.
Tingley, D.D., 2012. Design for Deconstruction: An Appraisal PhD Thesis. The University of Sheffield.
Tukker, A., 2013. Product services for a resource-efficient and circular economy – a review. J. Clean. Prod. 97, 76–91.
UNEP, 2016. Greening the Building Supply Chain. . Job number: DTI/1753/PA [Retrieved 18 October 2016]. Available at http://www.unep.org/sbci/pdfs/greening_the_supply_chain_report.pdf.
USEPA, 2016. Advancing Sustainable Materials Management: 2014 Fact Sheet. United States Environmental Protection Agency (USEPA). [Retrieved 18 November 2016] Available at: https://www.epa.gov/sites/production/files/201611/documents/2014_smmfactsheet_508.pdf,EPA530-R-17-01.
Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., Lahdesmaki, K., 2010. Moisture and bio-deterioration risk of building materials and structures. J. Build. Phys. 33, 201–224 No. 3.
WRAP, 2013. Built Environment Circular Economy. [Retrieved 13 July. 2017] Available at: http://www.wrap.org.uk/sites/files/wrap/WRAP%20Built%20Environment%20%20Circular%20Economy%20Jan%202013.pdf.
Wang, J., Li, Z., Tam, V.W., 2014. Critical factors in effective construction waste minimization at the design stage: a Shenzhen case study, China. Resour. Conserv. Recycl. 82, 1–7.
Webster, M.D., Costello, D., 2005. Designing structural systems for deconstruction. In: How to Extend a New Building's Useful Life and Prevent It from Going to Waste When the End Finally Comes. Greenbuild Conference Atlanta, GA.
Wordsworth, P., Lee, R., 2001. Lee's Building Maintenance Management. Blackwell Science, London.
Wu, W., Issa, R.R.A., 2014. BIM execution planning in green building projects: LEED as a use case. J. Manage. Eng. 31 (1). http://dx.doi.org/10.1061/(ASCE)ME.1 943–5479.0000314.
Xie, M., Lai, C.D., 1996. Reliability analysis using an additive Weibull model with bathtub-shaped failure rate function. Reliab. Eng. Syst. Saf. 52 (1), 87–93. http://dx.doi.org/10.1016/0951-8320(95)00149-2.
Xie, M., Tang, Y., Goh, T.N., 2002. A modified Weibull extension with bathtub-shaped failure rate function. Reliab. Eng. Syst. Saf. 76 (3), 279–285. http://dx.doi.org/10.1016/S0951–8320(02)00022–4.
Zeng, X.D., Tan, J., 2006. BIM based on intelligent parametric modeling technology [J]. J. Chongqing Univ. 6, p.027 Natural Science Edition.