Reusability Analytics Tool for End-of-life Assessment of Building Materials in a Circular Economy

Abstract

In a circular economy, the goal is to keep materials values in the economy for as long as possible. For construction industry to support the goal of the circular economy, there is the need for materials reuse. However, there is little or no information about the amount and quality of reusable materials obtainable when buildings are deconstructed. The aim of this study, therefore, is to develop a reusability analytics tool for assessing end-of-life status of building materials.

A review of the extant literature was carried out to identify the best approach to modelling end-of-life reusability assessment tool. The reliability analysis principle and materials properties were used to develop the predictive mathematical model for assessing building materials performance. The model was tested using the case study of a building design and materials take-off quantities as specified in the bill of quantity of the building design.

The results of analytics show that the quality of the building materials varies with the building component. For example, from the case study, at the 80th year of the building, the qualities of the obtainable concrete from the building are 0.9865, 0.9835, 0.9728 and 0.9799 respectively from the foundation, first floor, frame and stair components of the building.

The results of this tool will among others serve two purposes namely: (i) provides a useful monitoring tool for the asset maintenance companies to closely monitor the performance of a building. (ii) provides decision support service to the estate agents in determining the status and future worth of a building.

As a contribution to the concept of circular economy in the built environment, the tool provides a foundation for estimating the quality of obtainable building materials at the end-of-life based on the life expectancy of the building materials. This tool will be useful in forecasting the amount and quality of possible reusable and disposable materials from a deconstruction and demolition process.

Keywords: Reusability, building materials, end-of-life, recyclability, building component, demolition, deconstruction.

1 Introduction

The end-of-life performance of buildings is dependent on the performance characteristics of the individual component that makes up the building (Wordsworth and Lee, 2001). It is a function of the performance characteristics of the different building material that makes up the building components. The building material level of performance of buildings is a significant means through which buildings are evaluated as they approach their end-of-life. The recoverable materials at the end-of-life of buildings have two routes namely reusable (direct reuse and recycle) and waste to landfill (Thormark, 2006). Therefore, the reusability of different building materials that make up a building is an essential factor that influences end-of-life performance of buildings. However, no adequate attention has been given to the consideration of the reusability of building materials as a measure of end-of-life performance of buildings. This is due majorly to non-availability of adequate information to designers and engineers at the design stage. Although, according to Eastman *et al*. (2011), the issue of having reliable and adequate information available to designers is currently being partly addressed by the use of Building Information Modelling (BIM), little or no consideration is given to the reusability and recyclability of the recoverable materials at the end-of-life of building in BIM.

The concept of sustainability and green environment have been used interchangeably to describe various approaches and methods used to evaluate the performance of buildings in respect to their impact on the environment. The Building Research Establishment (BRE) developed the BRE Environmental Assessment Method (BREEAM) as part of the code for sustainable built environment in the UK (BRE, 2016). The Leadership in Energy and Environmental Design (LEED), is the instrument developed by the US Green Building Council to transform the way buildings are designed, built and managed in order to enable environmentally, socially responsible, healthy and prosperous environment that promotes good quality life (Webster, 2010). In Japan, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) is an assessment tool that is used to evaluate building performance (Fowler and Rauch 2006). A commonly used environmental and sustainability measurement tool in Australia, New Zealand and South Africa is the Green Star (Roderick, *et al*., 2009; Nguyen and Altan, 2011). Green Building Tool (GBTool) is a method used to assess the potential energy and environmental performance of a building project. It is a product of a worldwide collaborative effort to build an environmental assessment tool that takes care of controversial aspects of building performance and allows participating countries to selectively draw ideas to either incorporate into or modify the tool to reflect regional conditions and context. (Cole and Larsson, 2002; Fowler and Rauch, 2006). The criteria used by most of the rating systems in the evaluation of the performance of the building are similar. The criteria, primarily include energy consumption, water efficiency, material use and indoor environmental quality (Azhar *et al.*, 2011). All the existing tools for measuring the performance of building lack the capacity to estimate the end-of-life performance of building as a whole and in terms of individual material that makes up the building.

The aim of this study therefore, is to develop a tool for assessing the reusability level of building materials at the end-of-life of buildings. The specific objectives are as listed below:

i. To develop a mathematical model for assessing reusability level of building materials.
ii. To test the performance of the model, using a case study building design.

The rest of the paper is organised as follows: The literature review is covered in sections 2 and 3, where building materials requirements for circular economy support and factors that affect reusability of building materials are discussed. A detail description of the methodology, model simulation and evaluation are presented in sections 4. Discussion of the results is presented in section 5. Section 6 ends the paper with conclusion, limitation and areas of further research.

2 Building Materials Requirement for Effective Circular Economy

The key goal of a Circular Economy is to ensure that the added values in products are kept within the economic circle for as long as possible to avoid waste generation to landfill. Figure 1 shows the phases that materials go through in different form in a circular economy model. Each of the phases according to the 2014 Communication of the European Commission (COM, 2014) presents opportunities in term of reducing costs and dependence on natural resources. The goal of a circular economy is to limit new material extraction from the environment to the minimum possible while keeping the extracted material in the economy for as long as possible through residual waste reduction. There has been a number of strategies espoused in respect of building materials in a circular economy. Circular design**,** i.e., improvements in material selection and product design standardisation/modularisation of components, purer material flows, and design for easier disassembly are presented in Ellen Macarthur Foundation (EMF) report on “Towards the Circular Economy” (EMF, 2013). Design out waste, durable material selection, reduction in the use of energy in production and operation phase of building materials are some the strategies identified in COM (2014). Repurposing and adaptive reuse of buildings has been identified as a source of reduction in the environmental, social and economic costs of urban development and expansion. (Sfakianaki and Moutsatsou 2015; Assefa and Ambler, 2017).

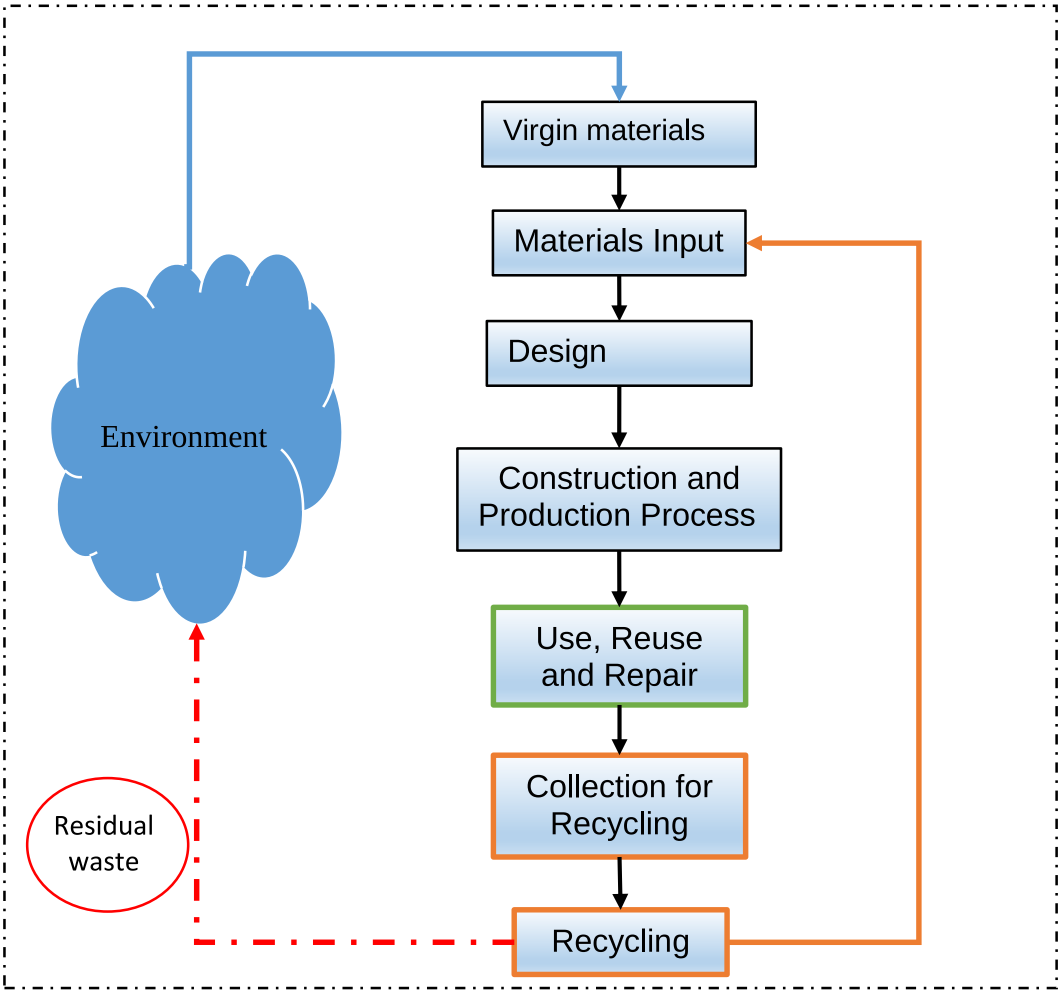

Figure 1: Different Phases in a Circular Economy Model

Apart from encouraging a high level of regional and domestic competitiveness through an increase in the effectiveness of resource allocation, resource utilization and productivity, the circular economy model leads to a reduction in the negative impact on the environment. This reduction in negative impact on the environment is by way of redesigning of the industrial structure in an ecological way. The circular economy model also facilitates the creation of additional employment opportunities, equals distribution of economic growth and improvement of the well-being of people (Morgan and Mitchell, 2015; Su et al., 2013).

3 Factors that affect Reusability of Building Materials at the End-of-life

There has been a lot of research efforts in the area of construction and demolition waste reduction through diversion of end-of-life waste of building from landfills. One of such efforts is the design for deconstruction (Akinade et al., 2016; Kibert, 2003) also known as design for disassembly (Crowther, 2005). The reusability (i.e. direct reuse and recycle) of the recovered building materials is however affected by factors such as environmental (Viitanen *et al.*, 2010), design and construction, operation and management factors (Kibert, 2003; BCIS, 2006). The choice of materials in building components (e.g. concrete in the foundation, timber in the stairs) determines whether the materials will be reusable as recovered or recycled into another kind of material for use in other components of the building. Whether a building is demolished, deconstructed or repurposed is also a major factor affect the reusability of building materials (Assef and Ambler, 2017). Other factors are the economy, regulation and incentives. The economics of the region where building materials are to be reused as well as the economics of the people in the region and the economics of businesses are all contributing factors to the reusability of recovered building material (Kibert, Chini, & Languell, 2001).

The environmental factors are natural factors that impact on the performance of building materials. Other factors are mostly as a result of human activities which influence the environmental condition around the building materials thereby indirectly contributing to the environmental influence on the materials. According to Viitanen *et al.* (2010), the natural ageing and eventual damage of building materials due to different chemical, physical, and biological processes can take place in the lifecycle of buildings. Ageing of the building materials as a part of the environmental processes involves different chemical, mechanical, and biological reactions of the materials. In this work, however, it is assumed that the best practice is ensured in the design, construction, operation and management of the buildings and the life expectancy of the building materials as reported in BCIS (2006) are used for the model development.

4 Methodology

After a review of the literature on various schemes used to measure the sustainability properties of buildings, circular economy and factors that affect reusability of building materials at the end-of-life, it became clear that an objectivity-based methodology is required for the development of a tool for assessing end-of-life performance of building materials. This shows the need for a systemic operationalisation of practices in driving genuine understanding of actions (Gray, 2009). As stated in Creswell (2014), a positivist worldview is required for any study that needs a high level of objectivity in driving an acceptable consensus. This work is therefore positioned within an objectivist epistemology where a single "real reality" exists (Crotty, 1998). This perspective helps to operationalise concepts into measurable entities (Guba and Lincoln, 1994). Following the line of positivism, it is important to identify and collect relevant data that would inform the development of an objective mechanism (a mathematical model) to describe the end-of-life characteristics of buildings. As such, this study adopts a review of extant literature to extract historical building life expectancy data, mathematical modelling approach to demonstrate the relationships among the variables and case study design to test the performance of the model. The mathematical model formulated to assess the performance of building materials is based on the published data about the life expectancy of building materials in different parts of the building by the Building Cost Information Service (BCIS) of the Royal Institution of Chartered Surveyor (BCIS, 2006).

4.1 Model Development

In formulating the mathematical model, the following assumptions were made: (i) the building was designed and constructed with the best engineering practice and as such early failure of materials is not considered, (ii) the building is put to normal use and (ii) environmental conditions are within the expected limit. These assumptions are necessary for situating the materials in proper context and are the bases upon which life expectancy data used for the modelling were collected. Table 1 shows the typical life expectancy in years for some of the building materials. The building materials column of the table contains the list of the building materials, part of the building where the materials are contained are listed as the building component column in the table. From the data, it is evident that building materials behave differently in different components of the building. That is why there is variation in the life expectancy of the same materials in different building component. For example, steel has a life expectancy of 73years when used in building frame and 58years when used in building stairs.

The reusability assessment of building material R_m is therefore modelled as an exponential function of the age of the building as shown in the equation 1. Table 2 shows the parameters used in the modelling and their meaning. The choice of the exponential function in this work is an adaptation from Akanbi et al. (2018) where the whole-life performance of a building is defined as an exponential function of time and other factors. To evaluate the model, a case study approach was adopted with the use of the take-off materials quantities for assessing the performance of the model. The case study design used is a two-storey residential building located in the South West of the UK with a ground floor area of 491.49m^2. The detail design characteristics features are presented in Table 3.

Table: 1 List of few Building Materials and their Average Life Expectancy (BCIS, 2006)

SN	**Building Material**	**Building Component**	**Average Typical Life Expectancy (Years)**
1	Concrete	Substructure	77
2	Insitu Concrete	Upper Floors	75
3	Precast Concrete	Upper Floor	72
4	Concrete	Frame	70
5	Steel	Frame	73
6	Timber	Frame	68
7	Concrete	Stairs	73
8	Steel	Stairs	58
9	Softwood	Stairs	62
10	Hardwood	Stairs	75
11	Aerated Lightweight Block	External wall	62
12	Dense Aggregate Block	External wall	72
13	Class B Engineering Brick	External wall	93
14	Machine made Facing Brick	External wall	79
15	PVC Cladding	External Wall	29
16	Galvanised Steel	External Wall	39
17	Precast Concrete	External Wall	60
18	Softwood Stud and Plasterboard	Internal Wall	56
19	Steel: De-mountable Partition	Internal Wall	31
20	Glass: De-mountable Partition	Internal Wall	28

Table 2: Description of the Model Parameters

Notation	Description
R_m	Reusability level of building material *m*
α_m	Life expectancy of building material *m*
t	Age of building in year
β	Reusability level measurement range ($0 \leq R_m \leq \beta$)
R_c	Reusability level of building component *c*
R_B	Overall Reusability level of Building

Table 3: Characteristic Feature of the Case Study Building

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

$$R_m = \beta - e^{t-\alpha_m} \qquad 1$$

Where R_m is the reusability value of building material *m* at age *t* of the building, α_m is the life expectancy of material *m*, *t* is the age of the building and β is the maximum value of the performance metric. A value of $\beta = 100$ implies that R_m ranges between 0 and 100 i.e. it is measured in percentage. After establishing the mathematical function for the material level computation of the reusability, the building component level computation is modelled as a function of its constituent materials as shown in equation 2. From the equation, R_c is the sum of the reusability values of the materials that make up the building component and *n* is the number of building materials that make up the building component. For example, the reusability value of a wall that is made up three materials is the sum of the reusability values of each of the three materials that make up the wall.

$$R_c = \sum_{i=1}^{n} R_{m_i} \qquad 2$$

The reusability value of the whole building at the end-of-life of a building is the sum of the reusability values of the building components that make up the whole building. This is shown in equation 3. From the equation, R_B is the reusability value of the building at any time during its lifecycle and *n* is the number of building components that make up the building. The whole building reusability value is a function of the performance of the individual component that makes up the building which is itself a function of the materials that make up the component. For explanation purpose, equation 3 is expanded to reflect the material level representation as shown in equation 4. Equation 5 is a compact representation of equation 4.

$$R_B = \sum_{j=1}^{n} R_{c_j} \qquad 3$$

$$R_B = R_{c_1} + R_{c_2} + R_{c_3} + R_{c_4} + \cdots + R_{c_c}$$

$$R_B = (R_{m_1} + R_{m_2} + R_{m_3} + \cdots + R_{m_m})_1 + (R_{m_1} + R_{m_2} + R_{m_3} + \cdots + R_{m_m})_2 + \cdots (R_{m_1} + R_{m_2} + R_{m_3} + \cdots + R_{m_m})_c \qquad 4$$

Therefore

$$R_B = \sum_{j=1}^{c} \sum_{i=1}^{m} R_{c_j} R_{m_i} \qquad 5$$

4.2 Model Simulation

To get an insight into the functioning of the mathematical model formulated above, it is necessary to simulate the model on a typical data set. The simulation experiment was run in Matlab environment for selected building materials of the chosen building component. Based on the life expectancy data shown in table 1, The model was simulated for building age that ranges from 0 – 140 years. Figures 2 – 5 show the behaviour of different building materials within different building component. It is clear from the figures that the reusability value of building materials begins to depreciate just about the end of their life expectancy. This is in line with the behaviour of materials generally (Almalki and Yuan, 2013; Carrasco et al., 2008; Xie et al., 2002; Xie and Lai, 1996).

4.3 Building Materials End-of-life Assessment

An objective scheme for the end-of-life assessment of the quality of buildings materials is developed based on the reusability performance of the building. This end-of-life assessment scheme will serve two purposes. It will help to determine the burn-in time of building materials while the building is still in use. It will also provide information about the quality of the recoverable materials from the building after deconstruction at the end-of-life of the building. The systematic assessment will provide an objective tool for measuring the quality of the materials that are recovered from a building at the end-of-life.

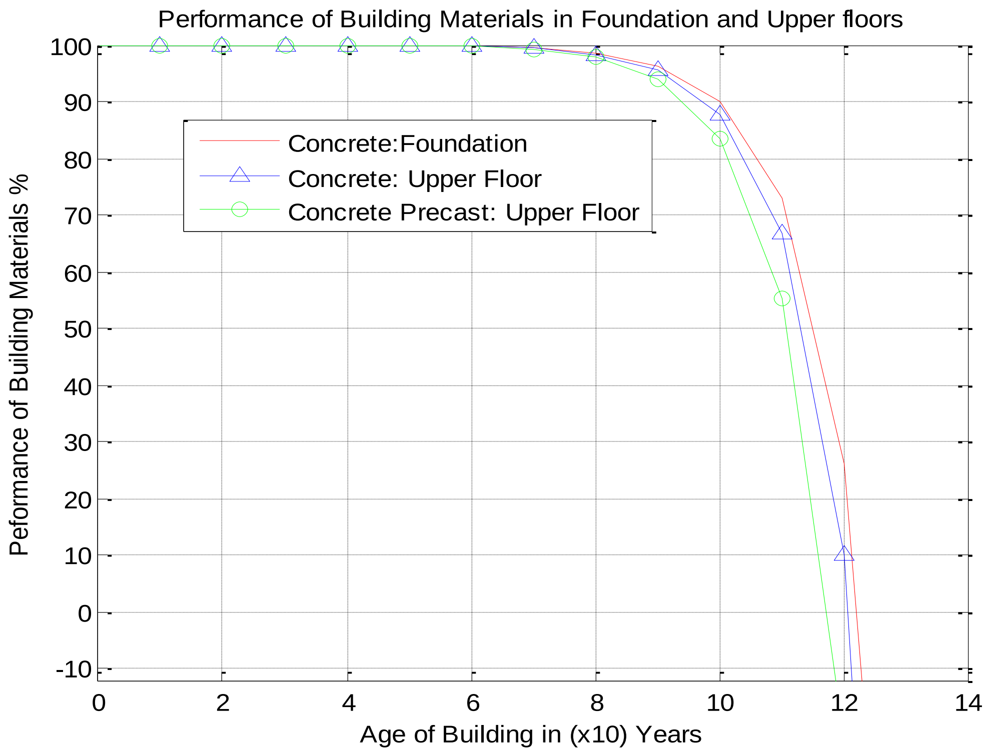

Figure 2: Performance of Concretes in Foundation and Upper Floors

Figure 3: Performance of Concrete, Steel and Timber in Frame Structure

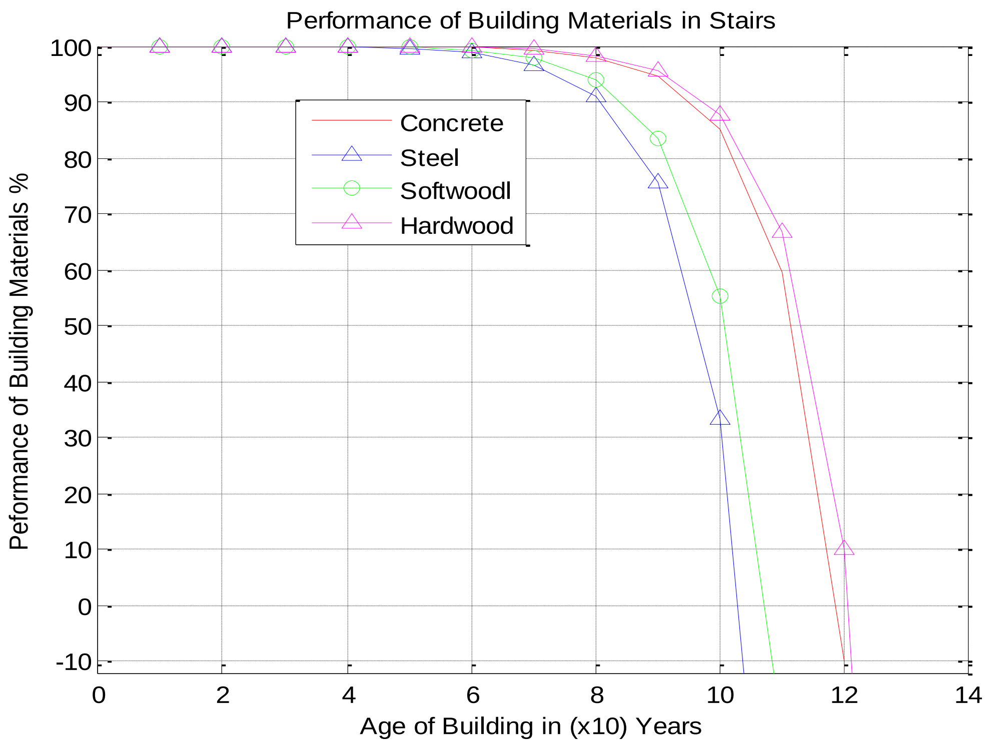

Figure 4: Performance of Concrete, Steel, Softwood and Hardwood in the Stairs

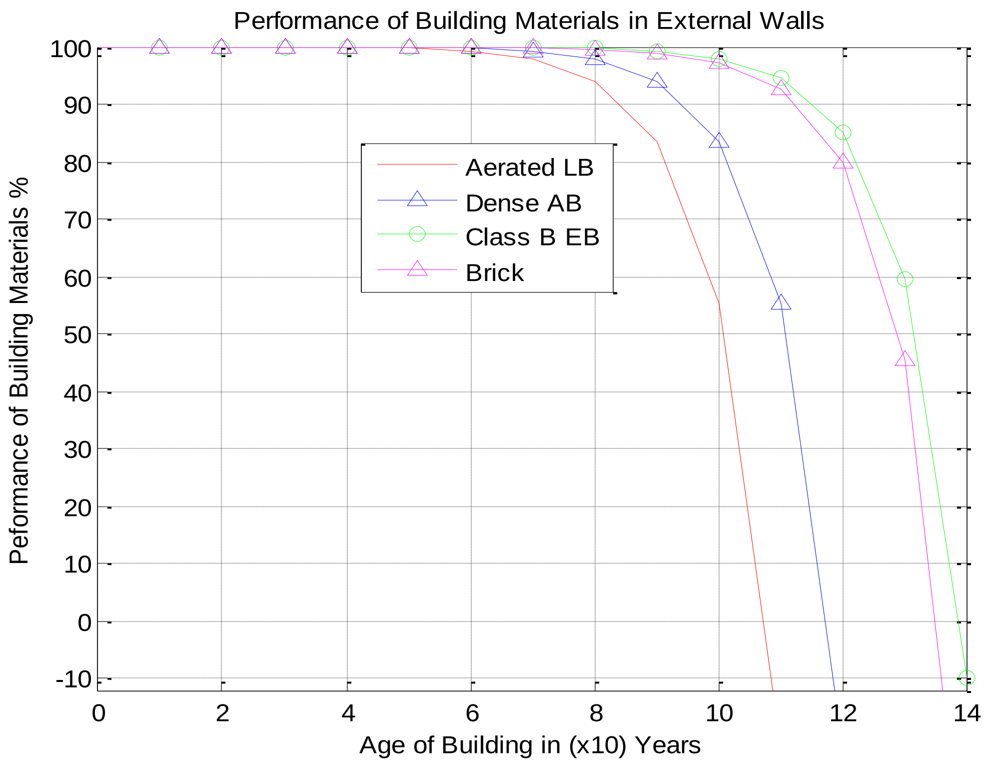

Figure 5: Performance of Aerated Lightweight Block (LB), Dense Aggregate Block (AB), Class B Engineering Brick (EB) and Facing Brick.

Equation 6 is devised to generate a grading system for measuring the quality of recoverable materials throughout the life cycle of building. From the equation, *Q(t)* is the quality of the recoverable materials and it ranges between 0 and 1, i.e. ($0 \leq Q(t) \leq 1$). A quality grade of 1 indicates that the recovered materials are of the best quality and a grade of 0 is an indication of materials with very low quality. Substituting equation 1 into equation 6 produces equations 7 and 8. Therefore, given the age of building *t* in years, the life expectancy α_m of the material *m* in years and the maximum performance obtainable β, the quality *Q(t)* of the expected material *m* to be recovered is obtained with equation 8.

$$Q(t) = \frac{R_m(t)}{\beta} \qquad 6$$

$$Q(t) = \frac{\beta - e^{t-\alpha_m}}{\beta} \qquad 7$$

$$Q(t) = 1 - \frac{e^{t-\alpha_m}}{\beta} \quad 8$$

Based on the quality of materials equations above (equation 8), an objective material quality grade range is proposed to enable classification of the materials appropriately. Table 4 shows the quality range and its corresponding grade. The corresponding destination of the recovered materials in each of the range is also shown in the table. It is important to note that some building materials are not directly reusable irrespective of their quality, they need to go through recycling before they could be useful, an example of such materials is concrete. Concretes are generally not reusable directly, they are usually recycled for use in other sectors of the construction industry such as for road pavement. Materials with $Q(t)$ value between 0.8 and 1.0 are considered to be of highest grade possible and are categorised as having grade quality A. This implies that such materials if carefully removed from the building will be reusable directly. This category of materials could also be considered for up or down cycling if there is no immediate need for it. It should also be noted that some building materials that fall under the category that is meant to go to landfill could also be recycled in order to reduce the amount of waste that goes to landfill, although this may be at an additional cost.

Table 4: Recoverable Materials Quality Classification

Quality Range	Quality Grade	Quality Colour	Destination
1.00 – 0.80	A	Green	Reuse
0.79 – 0.60	B	Blue	Recycle
0.59 – 0.40	C	Yellow	Recycle
0.39 – 0.00	D	Red	Landfill

4.4 Model Evaluation

To evaluate the mathematical model developed, a real-life building design with detail information about the material take-off of some selected building materials is used as the case study. The material take-off is obtained from the bill of quantity generated from the design. The take-off quantities of selected building materials of the case study building design are shown in table 5. The take-off materials quantities considered are those of foundation, floors, frame, stair and walls. Using the equation 1 for the estimation of the reusability performance of each material and equation 8 to estimate the quality of the recoverable material, the results obtained are shown in tables 6 – 11. Based on the recoverable materials quality classification described in table 4, the destinations (reuse, recycle or dispose) of the recoverable materials are also shown. The recoverable amount of building materials in percentage is obtained from equation 1 by making $\beta = 100$. The value obtained is then multiplied by the quantity of the material take-off to obtain recovered amount in tons. Equation 8 is then applied to obtain the quality of the recoverable materials as the building approaches its end-of-life.

Table 5: Take-off quantities of selected building materials of the case study building

Building Component	**Building Materials**	**Quantity (tons)**
Foundation	Concrete	75000
First Floor	Concrete	67000
Frame	Concrete	45000
Stairs	Concrete	25000
External walls	Dense Aggregate Block	3400
Internal walls	Softwood Stud and Plasterboard	5000
	Total	220,400

Table 6: End-of-life value of concrete at the foundation level

Building Component: Foundation		**Building Material: Concrete**		**Take-off quantity: 75,000 tons**	
Age of Building (Year)	**Recoverable Amount (%)**	**Recoverable Amount (tons)**	**Recoverable Materials Quality**	**Reusable (direct reuse + recycle) (tons)**	**Landfill Amount (tons)**
0	99.9995	74,999.66	1.0000	74,999.66	0.34
10	99.9988	74,999.08	1.0000	74,999.08	0.92
20	99.9967	74,997.49	1.0000	74,997.49	2.51
30	99.9909	74,993.18	0.9999	74,993.18	6.82
40	99.9753	74,981.46	0.9998	74,981.46	18.54
50	99.9328	74,949.60	0.9993	74,949.60	50.40
60	99.8173	74,862.99	0.9982	74,862.99	137.01
70	99.5034	74,627.56	0.9950	74,627.56	372.44
80	98.6501	73,987.61	0.9865	73,987.61	1,012.39
90	96.3307	72,248.03	0.9633	72,248.03	2,751.97
100	90.0258	67,519.36	0.9003	67,519.36	7,480.64
110	72.8874	54,665.52	0.7289	54,665.52	20,334.48
120	26.3002	19,725.15	0.2630	19,724.15	55,274.85
130	0.0000	0.0000	0.0000	0.00	75,000.00

Table 7: End-of-life value of concrete at the first-floor level

Building Component: First Floor		Building Material: Concrete		Take-off quantity: 67,000 tons	
Age of Building (Year)	Recoverable Amount (%)	Recoverable Amount (tons)	Recoverable Materials Quality	Reusable (direct reuse + recycle) (tons)	Landfill Amount (tons)
0	99.9994	66,999.63	1.0000	66,999.63	0.37
10	99.9985	66,998.99	1.0000	66,998.99	1.01
20	99.9959	66,997.26	1.0000	66,997.26	2.74
30	99.9889	66,992.56	0.9999	66,992.56	7.44
40	99.9698	66,979.77	0.9997	66,979.77	20.23
50	99.9179	66,945.00	0.9992	66,945.00	55.00
60	99.7769	66,850.50	0.9978	66,850.50	149.50
70	99.3935	66,593.62	0.9939	66,593.62	406.38
80	98.3513	65,895.36	0.9835	65,895.36	1,104.64
90	95.5183	63,997.27	0.9552	63,997.27	3,002.73
100	87.8175	58,837.73	0.8782	58,837.73	8,162.27
110	66.8845	44,812.65	0.6688	44,812.65	22,187.35
120	9.9829	6,688.52	0.0998	6,688.52	60,311.48
130	0.0000	0.0000	0.0000	0.00	67,000.00

Table 8: End-of-life value of concrete in the frame structure

Building Component: Frame		Building Material: Concrete		Take-off quantity: 45,000 tons	
Age of Building (Year)	Recoverable Amount (%)	Recoverable Amount (tons)	Recoverable Materials Quality	Reusable (direct reuse + recycle) (tons)	Landfill Amount (tons)
0	99.9991	44,999.59	1.0000	44,999.59	0.41
10	99.9975	44,998.88	1.0000	44,998.88	1.12
20	99.9933	44,996.97	0.9999	44,996.97	3.03
30	99.9817	44,991.76	0.9998	44,991.76	8.24
40	99.9502	44,977.60	0.9995	44,977.60	22.40
50	99.8647	44,939.10	0.9986	44,939.10	60.90
60	99.6321	44,834.45	0.9963	44,834.45	165.55
70	99.0000	44,550.00	0.9900	44,550.00	450.00
80	97.2817	43,776.77	0.9728	43,776.77	1,223.23
90	92.6109	41,674.92	0.9261	41,674.92	3,325.08
100	79.9145	35,961.51	0.7991	35,961.51	9,038.49
110	45.4018	20,430.83	0.4540	20,430.83	24,569.17
120	0.0000	0.00	0.0000	0.00	45,000.00
130	0.0000	0.00	0.0000	0.00	45,000.00

Table 9: End-of-life value of concrete at the stairs

Building Component: Stair		Building Material: Concrete		Take-off quantity: 25,000 tons	
Age of Building (Year)	Recoverable Amount (%)	Recoverable Amount (tons)	Recoverable Materials Quality	Reusable (direct reuse + recycle) (tons)	Landfill Amount (tons)
0	99.9993	24,999.83	1.0000	24,999.83	0.17
10	99.9982	24,999.54	1.0000	24,999.54	0.46
20	99.9950	24,998.75	1.0000	24,998.75	1.25
30	99.9864	24,996.61	0.9999	24,996.61	3.39
40	99.9631	24,990.78	0.9996	24,990.78	9.22
50	99.8997	24,974.94	0.9990	24,974.94	25.06
60	99.7275	24,931.87	0.9973	24,931.87	68.13
70	99.2592	24,814.80	0.9926	24,814.80	185.20
80	97.9862	24,496.56	0.9799	24,496.56	503.44
90	94.5261	23,631.51	0.9453	23,631.51	1,368.49
100	85.1203	21,280.07	0.8512	21,280.07	3,719.93
110	59.5527	14,888.17	0.5955	14,888.17	10,111.83
120	0.0000	0.0000	0.0000	0.00	25,000.00
130	0.0000	0.0000	0.0000	0.00	25,000.00

Table 10: End-of-life value of dense aggregate block in the external wall

Building Component: External Wall		Building Material: Dense Aggregate Block		Take-off quantity: 3,400 tons	
Age of Building (Year)	Recoverable Amount (%)	Recoverable Amount (tons)	Recoverable Materials Quality	Reusable (direct reuse + Recycle) (tons)	Landfill Amount (tons)
0	99.9993	3,399.97	1.0000	3,399.97	0.03
10	99.9980	3,399.93	1.0000	3,399.93	0.07
20	99.9945	3,399.81	0.9999	3,399.81	0.19
30	99.9850	3,399.49	0.9999	3,399.49	0.51
40	99.9592	3,398.61	0.9996	3,398.61	1.39
50	99.8892	3,396.23	0.9989	3,396.23	3.77
60	99.6988	3,389.76	0.9970	3,389.76	10.24
70	99.1813	3,372.16	0.9918	3,372.16	27.84
80	97.7745	3,324.33	0.9777	3,324.33	75.67
90	93.9504	3,194.31	0.9395	3,194.31	205.69
100	83.5554	2,840.88	0.8356	2,840.88	559.12
110	55.2988	1,880.16	0.5530	1,880.16	1,519.84
120	0.0000	0.00	0.0000	0.00	3,400.00
130	0.00	0.00	0.0000	0.00	3,400.00

Table 11: End-of-life value of softwood stud and plasterboard in the internal wall

Building Component: Internal Wall		Building Material: Softwood Stud and Plasterboard		Take-off quantity: 5,000 tons	
Age of Building (Year)	Recoverable Amount (%)	Recoverable Amount (tons)	Recoverable Materials Quality	Reusable (direct reuse + Recycle) (tons))	Landfill Amount (tons)
0	99.9963	4,999.82	1.0000	4,999.82	0.18
10	99.9899	4,999.50	0.9999	4,999.50	0.50
20	99.9727	4,998.63	0.9997	4,998.63	1.37
30	99.9257	4,996.29	0.9993	4,996.29	3.71
40	99.7981	4,989.91	0.9980	4,989.91	10.09
50	99.4512	4,972.56	0.9945	4,972.56	27.44
60	98.5082	4,925.41	0.9851	4,925.41	74.59
70	95.9448	4,797.24	0.9594	4,797.24	202.76
80	88.9768	4,448.84	0.8898	4,448.84	551.16
90	70.0359	3,501.79	0.7004	3,501.79	1,498.21
100	18.5491	927.46	0.1855	0.00	5,000.00
110	0.0000	0.0000	0.0000	0.00	5,000.00
120	0.0000	0.0000	0.0000	0.00	5,000.00
130	0.0000	0.0000	0.0000	0.00	5,000.00

Tables 6 and 7 show the end-of-life values of building materials in the foundation and the first floor components of the building. The end-of-life values of building materials in the frame and stairs building components are shown in tables 8 and 9 while end-of-life values of building materials in the wall (internal and external) component of building are shown in tables 10 and 11. From the results, it is noted that the structural components of building retain some quality beyond 100years whereas the quality of non-structural components material such as softwood stud and plasterboards degrade to near zero before 100years. Although the performance of building materials and component is a function of other factors (such as occupancy behaviour and activities) that are beyond the scope of this study, the reusability is developed based on the standard construction and normal operation of buildings.

5 Discussion

The reusability analytics tool developed in this work is a mathematical solution that provides the basis for assessing end-of-life reusability level of building materials based on their typical life expectancy as documented in BCIS (2006). The results of the evaluation of the model with the case study building's design and material take-off show that building components determine how building materials fare through the life cycle of building (Akinade et al., 2015). This is due to the fact that building components are exposed to different environmental and operational conditions (Viitanen *et al.,* 2010). For example, as shown in Table 6, the quality of the recoverable concrete material from the foundation component of the case study building design degrades to grade B just after 100 years and the rate of diminishing in quality becomes rapid after 110 years. At 120 years, the quality of the recoverable concrete has dropped to grade D based on the classification in Table 4. According to the classification in Table 4, a concrete foundation will produce end-of-life concrete materials that would mostly end up in landfills after 120 years. However, this could be down-cycled into aggregates and materials for roadbeds (Nakajima et al., 2005) to prevent the materials from going to the landfill. In the same vein, the quality of the concrete material recoverable from stairs degrades to grade B after 100 years. However, at 110 years, the quality degrades to grade C and at 120 years, the quality becomes zero. These results show that the effect of environmental and operational factors on the concrete materials in the stairs is more than that of the concrete materials in the foundation component.

The results presented in tables 6 – 11 show that as the age of the building increases, the quality of recoverable materials diminishes and so the probability of direct reuse of the materials. It should be noted that the probability of a direct reuse of recoverable materials from building at the end-of-life is dependent not only on the quality of the material, other factors such as demand and availability of space onsite or nearby to store the materials are major requirements for building materials direct reuse.

The reusability analytics tool presented in this work could be used by a number of practitioners in the building construction and demolition industry. To the designer, it is a tool that could be used to evaluate the potential end-of-life performance of buildings design, thereby assisting in comparing alternative design and making appropriate decisions. The regulators in the built environment could use the tool to determine when and where to create temporary storage for storing recoverable materials from buildings that are to be deconstructed/demolished. This would assist in reducing the carbon footprint of the end-of-life activities of buildings. The demolition engineers could use the tool to determine the worth of a building before it is deconstructed/demolished.

The results of the model evaluation show that the end-of-life performance of the whole building is dependent on the performance of the individual materials that make up the building components. Therefore, the optimal end-of-life value of a building is dependent on the end-of-life value of the structural materials with the least life expectancy. This is because the failure of a building material will lead to an untimely failure of the component that contains the material.

According to Akanbi et al. (2018), the main objective of a circular economy is to use and reuse materials. The reusability analytics model provides an opportunity for building designers to simulate the whole life performance of building materials and make necessary adjustments to the design thereby leading to buildings with efficient materials recovery for the circular economy. The results from the case study show the rate at which building materials quality degrade with age. While, several works have been done to enable BIM support for sustainability and circular economy principle (Liu et al., 2015; Jalaei and Jrade, 2015; Alwan et al., 2017). This work provides the mathematical foundation for integrating building materials reusability analytics to BIM software.

6 Conclusion

This study presented a mathematical model of building materials salvage value estimator based on the life expectancy data of building materials in use. The model was tested with a case study building design with corresponding take-off materials information. The take-off materials quantities of the selected building materials as obtained in the bill of quantities associated with the building design were used to evaluate the model. The results of evaluation of the model provide an efficient monitoring tool for building asset maintenance companies to closely monitor the performance of buildings and proactively develop maintenance plans based on the performance of the building materials over time. It also provides decision support service to the estate agents in determining the status and future worth of a building. The contribution of this study is therefore two-fold: (i) it provides a tool for forecasting the amount and quality of materials that are obtainable from buildings at the end of their life. It also provides information about the categories of the materials (i.e. reuse, recycle and dispose) from a deconstruction and demolition process; and (ii) it provides the basis for stakeholders in building construction to evaluate the performance of building designs with respect to the circular economy requirements.

This study has implications for both academic and industry practice. For academics, the study demonstrated the application of mathematical concepts to solve life problems (in this case, construction industry). It improves the understanding of how the prediction of the quality and quantity of building materials could be formulated into a computational model. For the industry practice, since circular economy is now being adopted in the UK and world over, this study provides a tool for estimating building materials performance to support practitioners in the construction and demolition industry (architects, building designers, engineers and planner). The availability of a material reusability analytics within BIM environment will improve its acceptability and usability among industry practitioners. The integration of this tool into a BIM software is the next stage in our development effort. This will allow for easy exchange of data between the tool and existing BIM software solutions.

The scope of this work is limited to building materials from the structural components of a building only. Other components such as fitting, the nature of bonding of materials and facades are not considered. However, the model could be easily extended to these other components.

Acknowledgment

The authors would like to acknowledge and express their sincere gratitude to the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK (Grant Reference No. EP/N509012/1, Grant Application No. 54832–413479/File No. 102473) for providing the financial support for this study.

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