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A Conceptual Model for Assessing Circularity Potential of Building Materials at the Product Manufacturing Stage

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Abstract. *The construction industry presently accounts for 30% of natural resource extraction and 25% of solid waste generation. The prevailing economy is "Linear" which is summarised as take-make-dispose. On the contrary, the "circular economy" model is a systematic model to restore, regenerate and expand the lifecycle of materials. Most of the existing circularity assessment methods are focused on the end-of-life wastage of building materials while neglecting resource consumption and wastage at the product manufacturing stage. Further, these methods only consider direct material flows for assessing the circularity potential of building materials and overlook the indirect material flows associated with product manufacturing. There is a need to develop metrics to assess the circularity performance of building materials more holistically. Therefore, this study proposes a conceptual model to assess the circularity potential of building materials by analysing both direct and indirect material flow processes of the product manufacturing stage including raw material extraction, transportation, and manufacturing. The method used to design the conceptual model includes a comprehensive literature review in two stages. First, the existing circular assessment methods are reviewed to identify the methods used for assessing the circularity potential of building materials. Secondly, the circularity options are explored to develop the circularity metrics. According to the findings of this study, in the absence of a comprehensive method to assess the circularity potential of building materials, the life cycle assessment and material flow analysis are the most prominent circularity assessment methods used. Furthermore, circularity options such as industrial waste (by-products), biodegradability, biofuels, renewable energy, reusability, recoverability, recyclability and product life span are identified as the circularity metrics for building materials at the product manufacturing stage.*

Keywords: *Circular Economy; Building Materials; Resource Consumption and Waste; Circularity Metrics; Product Manufacturing Stage*

1 Introduction

Global raw material consumption accounts for 90 Gigatonnes today and has been predicted to be increased by double in 2060 as the expansion of the global economy and rising standard of living (The Organization for Economic Co-operation and Development (OECD), 2019). Simultaneously, global solid waste is anticipated to grow by 3.40 billion tonnes in 2050, which is presently 2.01 billion tonnes. The construction industry's contribution towards raw material consumption has accounted for nearly 30% and solid waste generation for 25% (Wahlström et al. 2020).

The circular economy has been identified as a new methodological approach that can reduce carbon emissions, biodiversity loss, waste, and pollution through the circulation of wastage of materials. Circulatory building material management can lead to reducing nearly 61% of material-related carbon emissions by expanding the life spans of building materials through reusing, recovering, and recycling strategies (United Nations Environment Programme, 2022). Measuring and reporting the circularity potentials of the building materials are yet at the infancy stage (Ellen MacArthur Foundation (EMF), 2015; Oluleye et al. 2022). Moreover, the existing circularity assessing tools only address direct material flow, i.e. the flow of main ingredients or components that go into manufacturing a product, in measuring circularity without considering any indirect material flow. The indirect material flow is arguably a missing scope in assessing circularity more holistically.

Therefore, this study aims to better understand the existing circular economy assessment tools, specifically on the methods used by the existing circular economy assessment tools and identify the options which can enhance the circularity potential of building materials at the product manufacturing stage for proposing a conceptual model for assessment.

2 Research Method

The research methodology followed in the study as illustrated in Figure 1.

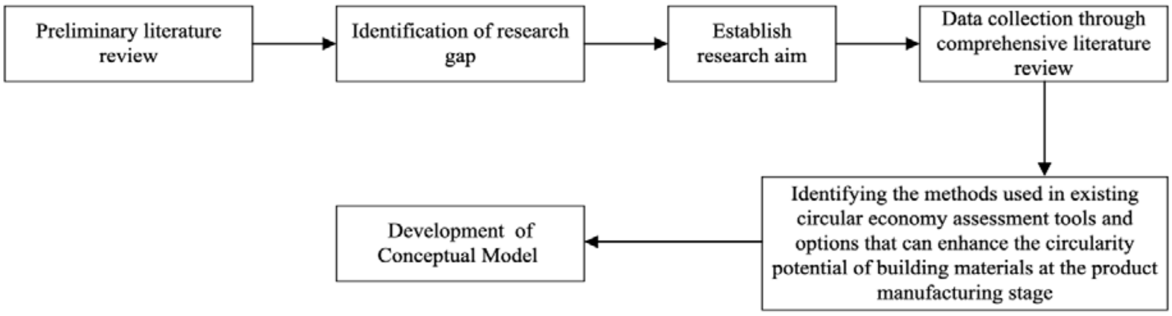

Figure 1. Research method.

The preliminary literature review revealed the need of developing circular economy assessment methods for building materials at the product manufacturing stage. Hence, this study has followed a comprehensive literature review to investigate the methods used by existing circular economy assessment tools and explore the options which can enhance the circularity potential of building materials at the product manufacturing stage for developing a conceptual model to assess the circularity potential of building materials at the product manufacturing stage.

3 Literature Review

The following section discusses important aspects of the circular economy, existing circular economy assessing tools, and options of building materials at the product manufacturing stage.

3.1 Circular Economy

The circular economy is a resilient systematic process of regenerating and restoration of nature by eliminating unnecessary finite resource consumption and wastage. Circulating materials or products at their highest potential through reusing, recovering, and recycling is the key driver of the circular economy. The materials or products are categorised according to the continuous flows of materials cycles in the circular economy, i.e. biological cycle and the technical cycle. The former refers to the process of biodegradation that the materials or products go through, while the latter is the progressive phases of re-using, recovering, and recycling (EMF, 2015).

3.2 Product Manufacturing Stage

The World Green Building Council (WGBC) (2019) has revealed that the "up-front carbon emissions" will be responsible for 20% of the entire carbon footprint which is 40% of new construction projects between 2019 and 2050. The "upfront carbon emissions" refer to the carbon footprint of the product manufacturing stage including raw material extraction, transport, and manufacturing (BS EN 15978: 2011). Addressing the reduction of upfront carbon at the product manufacturing stage through reducing resource consumption and wastage is critical and urgent (WGBC, 2019).

3.3 The Methods Used in the Existing Circular Economy Assessment Tools

The circular economy assessments estimate the potential of transition from a linear economy to a circular economy of building materials (Ellen MacArthur Foundation (EMF), 2015). There is a limited number of circular economy assessment tools existing as illustrated in Table 1.

Table 1. Existing Circular Assessing Tools.

No	Tools	Scope	Methods used			Source
			LCA	MFA	IOA	
1	Recyclability Assessment	Circularity of end-of-life wastage of building materials	√			(Roithner et al., 2022)
2	Environmental and Economic Assessment	Assessing regional level resource consumption and construction demolition waste	√	√	√	(Meglin et al., 2022)
3	Circular – LCA	Assessing the environmental impacts of circulated building components	√			(Van et al., 2021)
4	CirBIM Database	Data storage tool on circular building materials for BIM	√			(Göswein et al., 2022)
5	Material Passport	Data storage tool on end-of-life-wastage circularity of building materials	√			(Heinrich and Lang, 2020)
6	Resource Conservation Potential	Assessing the resource consumption saving potential through circulation of end-of-life wastage	√			(Tazi et al., 2021)
7	Material Circularity Indicator	Assessing the circularity of products through virgin material usage, unrecoverable waste, product longevity in general not building material specific	√	√		(Ellen MacArthur Foundation (EMF), 2015)
8	Building Circularity Index	Assessing the circularity of end-of-life wastage of building materials	√			(One Click LCA, 2023)

As indicated in Table 1, The Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Input-Output Analysis (IOA) have been identified as the methods used by the researchers and organizations for developing the tools for assessing the circularity of building materials.

3.3.1 Life Cycle Assessment (LCA)

LCA is a study of the compilation and evaluation of the unit inputs (products including any goods or services, materials, or energy flows: fuels and electricity), unit outputs (products, material, or energy flows), and the potential environmental impacts of a product throughout its life cycle stages. These life cycle stages are the product stage, use stage, end-of-Life stage and the circularity of end-of-life-wastage (BS EN ISO 14040: 2006+A1:2020).

3.3.2 Material Flow Analysis (MFA)

MFA is an assessment method which is used to analyse the differences in mass balances over time to identify the state and changes of material flow within a defined system (BS EN ISO 14051:2011).

3.3.4 Input-Output Analysis (IOA)

Input-Output Analysis is an economic analysis which is used to study the changes in the economy such as demand and supply including the direct and indirect interdependencies (Wixted et al, 2006).

In summary, LCA can be identified as the widely followed method for assessing circularity. However, there are considerable studies which have followed both LCA and MFA. This emphasises that these studies have considered both end-of-life wastage and mass balances of the material flows of a product when assessing the circularity. IOA has been used when integrating the economic assessments for circulated materials.

3.4 Options for Enhancing Circularity of Building Materials

The options which can enhance the circular economy are referred to as the circularity options here. These circularity options have been aligned with the aims of the Circular Economy as illustrated in Table 2.

Table 2. Options for enhancing Circular Economy

No	Circularity Option	Aims of circular Economy		Source
		Reducing resource consumption	Reducing wastage	
1	Recyclability		√	(European Commission, 2020)
2	Reusability		√	(OECD, 2021)
3	Recoverability		√	(OECD, 2021)
4	Biodegradability		√	(EMF, 2015)
5	Biofuels	√		(International Renewable Energy Agency, 2020)
6	Renewable energy	√		(United Nations, 2021)
7	By-products	√		(European Commission, 2018)
8	Life span of the product	√		(EMF, 2015)

3.4.1 Circularity options for reducing resource consumption of building materials

Biofuels and Renewable energy, by-products, and the life span of the products are the sources of saving finite resources. Biofuel and Renewable energy are derived from natural resources which are infinite and replenished over a human lifespan. (United Nations, 2021; International Renewable Energy Agency, 2020). Besides, By-products are incidental products which are resulted as the residues of a manufacturing process. These by-products can be utilised as raw materials for manufacturing processes. For instance, the utilization of fly ash for manufacturing geopolymer concrete (European Commission, 2018). The lifespan of a product emphasises the durability of the products that can resist from damaging and able to be reused or recycled at the end of their use. Hence, these options can enhance the circular potential of the building materials.

3.4.2 Circularity options for reducing wastage

Recyclability, Reusability and Recoverability are referred to as 3R strategies in the Circular Economy. These 3R strategies can be considered as capabilities of a product or material being reclaimed again fully or partially through wastage generated by the product, itself (European Commission, 2020). In addition to that Biodegradability of a product or material refers to being degradable biologically with the aid of microorganisms such as bacteria and fungi (Ellen MacArthur Foundation, 2015). Hence, these options can enhance the circularity potential of the building materials by circulating wastage as inputs for the product manufacturing process.

4. Conceptual Model

The prevailing research gaps in current circularity assessment tools as discussed in the literature review emphasise the importance of introducing a holistic methodology for assessing the circularity potential of building materials at the product manufacturing stage. As the existing tools analysed the direct material flows, this conceptual model analysed both direct and indirect material flows of the building materials at the product manufacturing stage including raw material extraction, transport and manufacturing processes. Besides the existing tools used LCA and MFA as the methods for measuring the circularity of end-of-life wastage of building materials and balancing the masses between inputs and end-of-life wastage of materials whereas this conceptual model used LCA and MFA to identify the direct and indirect material flow processes of the production stage. Further, the MFA is used to develop the circularity metrics in the proposed conceptual model by focusing on mass balances between the inputs and wastage derived at the product manufacturing stage of building materials. This section explains the methodology in detail of the proposed conceptual model.

The direct material flow and indirect material flow processes of the production stage have Been identified according to the LCA standard BS EN ISO 14040: 2006+A1:2020 and MFA standard BS EN ISO 14051:2011. The direct material flow processes include direct inputs supply (material and energy), Manufacturing Process and Output (Finished product). The indirect material flow processes include indirect inputs supply (ancillary inputs of production: material and energy), Manufacturing Process, and Output (Finished product). The sub-processes and inclusion areas have been identified along with the relevant circularity options for developing the circularity metrics as illustrated in Table 3.

Table 3. Analysis of direct and indirect material flows of building materials at the product manufacturing stage

Material flow	Main Process	Sub process	Inclusion areas of sub processes	Circularity options
Both direct and indirect	Inputs	Supply from virgin stock	Raw material extraction/ packaging /transportation	Biodegradability/ renewable energy/ recyclability/ Biofuels
		Supply from re-used stock	packaging /transportation	recyclability/ Biofuels/
		Supply from recovered stock	Recovering process	Renewable energy/ recyclability/ Biofuels

material flows		Supply from recycled stock	Processing/ remanufacturing/ packaging /transportation	Renewable energy/reusability/ recyclability/ Biofuels
	Manufacturing	All processes in manufacturing	Direct and indirect wastage	By-products/ recoverability of waste
	Output	Finished product/ Packaging	Finished product/ Packaging	Reusability/ life span of product/Recyclability

The mass of each circularity option has been considered for developing the metrics except the life span of the product. The life span of a product refers to the durability of a product. The illustration of circularity metrics has been categorised into Inputs, manufacturing, and output.

4.1 Inputs

Supply from virgin stock, recycled stock, re-used stock and recovered stocks can be identified as the sources of inputs for manufacturing a product. These all sources follow the sub-processes (extracting processes, packaging, and transport) and respective circularity assessing options as illustrated in Table 3. Therefore, each process has been analysed to calculate the overall circularity potential of inputs as explained below.

4.1.1 Circularity potential of supply of Virgin stock (V_{cp})

The mass of biodegradability and renewable energy is proposed as the metrics for assessing the circularity of the raw material extraction process. Further, the mass of recyclability content and the mass of utilization of biofuels is proposed for assessing the circularity of packaging and transportation respectively.

4.1.2 Circularity potential of supply of reused stock ($R1_{cp}$)

The mass of recyclability content and the mass of utilization of biofuels is proposed for assessing the circularity of packaging and transportation respectively.

4.1.3 Circularity potential of supply of recovered stock ($R2_{cp}$)

Energy recovery through solid wastes has been considered as the recovered stock. Therefore, the mass of recyclability content of packaging of solid waste, the mass of utilization of biofuels for transporting the solid waste, and the mass of renewable energy for recovering processes are proposed as the metrics for assessing the circularity of recovered stock.

4.1.4 Circularity potential of supply of recycled stock ($R3_{cp}$)

The mass of renewable energy, the mass of reusability content of the recycled stock, the mass of recyclability content of packaging and the mass of utilization of biofuels for transportation are proposed as the metrics for assessing the circularity of recycled stock.

Hence, the circularity potential of all inputs can be calculated through equation (1) below.

$$Inputs_{cp} \approx V_{cp} + R1_{cp} + R2_{cp} + R3_{cp} \qquad (1)$$

Circularity potential of Inputs ≈ Circularity potential of Virgin stock + Circularity potential of Reused stock + Circularity potential of Recovered stock + Circularity potential of recycled stock

4.2 Manufacturing Process

The Mass of By-products and other reusable, recoverable, waste is proposed as the circularity metrics measure the circularity potential of the manufacturing process as illustrated in equation (2).

$$Process_{cp} \approx M_{BP} + M_{RW1} + M_{RW2} + M_{RW3} \qquad (2)$$

Circularity potential of the manufacturing process ≈ Mass of By-products + Mass of reusable waste+ Mass of recoverable waste+ Mass of Recyclable waste

4.3 Output (Finished product)

The life span of the output, recyclability, and reusability content of the output at the end-of-life stage is proposed to measure the circularity potential of output as illustrated in equation (3). The life span of the output has been compared with the life span of a substitute product in the industry which is similar in nature. If the life span is higher against the substitute product, the circularity potential of the output is high and vice versa.

$$Output_{cp} \approx \{ (M_{R1} + M_{R2})\ X\ (L/L_{av})\} \qquad (3)$$

Circularity potential of output ≈ {(Mass of Reusability content+ Mass of recyclability content) x (Average life span of the output / average life span of the substitute product)}. The graphical representation of the conceptual model is interpreted in Figure 2.

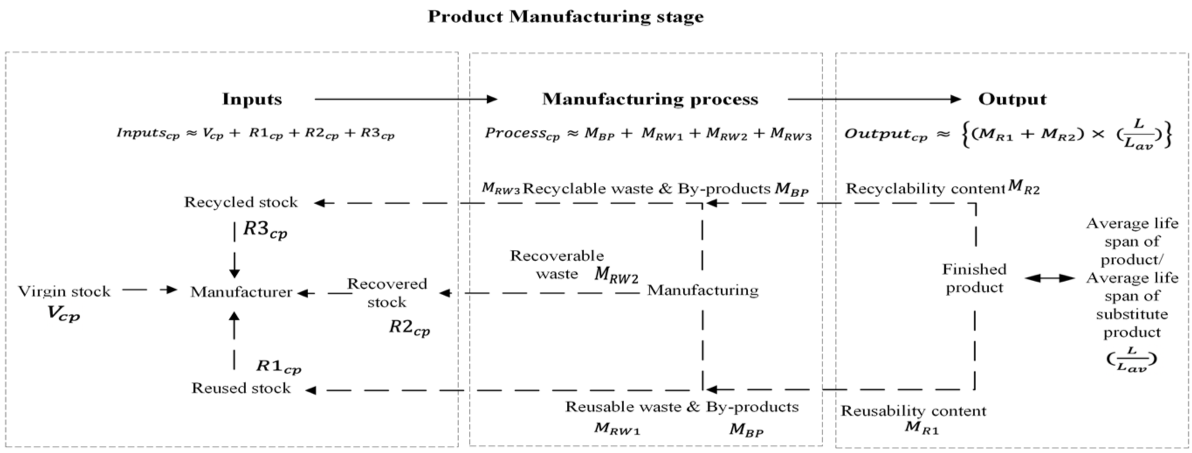

Figure 2. Conceptual Model

The graphical interpretation shows both direct and indirect material flows between each main process (Inputs-Manufacturing Process-Output) of the product manufacturing stage. Further, this graphical interpretation clearly shows the sources of resource consumption (inputs) and the circulation of waste such as recyclable waste, reusable waste, recoverable waste, and by-products as the inputs again for the manufacturing process of building materials.

5 Conclusions

The existing circular economy assessment tools have not properly analysed both direct and indirect material flow processes that can enhance the circularity potential of building materials. This results in an approximate circularity estimation of building materials. Hence, this study has proposed a conceptual model by analysing both direct and indirect material flows for assessing the circularity potential of building materials at the product manufacturing stage. The direct and indirect material flow analysis at the product manufacturing stage revealed net resource consumption and wastage of building materials. Also, this type of analysis can explore the areas where can circulate the wastage at the maximum potential which results in value addition for the circulation of wastage. Hence, this conceptual model will help the construction industry stakeholders to identify and evaluate the circularity potential of the building materials at the product manufacturing stage for better decision-making.

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