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ANALYTICAL REVIEW OF METHODOLOGICAL APPROACHES FOR MEASURING CIRCULARITY IN BUILDING RENOVATION

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Abstract

Circularity in construction industry requires understanding of the complex system dynamics, which are affected by various building layers and societal systems. While the existing building stock offers opportunities to enable re-looping of construction and demolition waste, the assessment of building circularity performance is not straightforward, due to lack of standard database, methods, and tools. This may lead to subjective interpretations by practitioners who rely on lifecycle assessment (LCA) approach complemented with circularity indicators (C-indicators) to know the level of circularity (LOC) of building materials, components, and elements. Thus, these C-indicators requires careful evaluation of the current methodological approaches. The aim of this paper is to map and evaluate the nexus between assessment methodologies highlighting their strengths, limitations, and areas of improvement. In this study, a complementary approach of systematic literature review and design research concept was used to classify seven primary aspects covering 18 key performance indicators, that impact the system thinking approach of the renovation project. The critical analysis of ten distinguished C-indicators show conditional, beneficial and trade-off relationships between various indicators. At the same time, the dynamic aspect of re-looping the resources is missing in these indicators and sustainability is accounted by complementing lifecycle impacts rather than coupling them. Results of this review highlight substantial gaps in C-indicators applicability for renovation projects with emphasis to formulate a practical guidance to assess recirculation of materials throughout the value chain.

Keywords: system thinking, built-environment, resource efficiency, environment impact assessment, comparative analysis

1 Introduction

Construction industry is responsible for 40% of raw material extraction and 35% of waste generation, which is the outcome of the dominant linear value chain. The transition from linear economy to circular economy (CE) is dependent on the complexity of the system and subsystems that are integrated between both technical and biological cycles for continuous functioning. While the built environment is interconnected to various infrastructural systems at micro, meso, and macro levels, the buildings are also a complex integration of spatial, technical, and material systems known as Brand's shearing layers which have different lifespan (Brand 1995).

To efficiently monitor the material salvaging potential in the renovation projects its performance evaluation is important. For instance, recirculation of materials may encourage recycling at the end-of-life scenario to incineration for energy recovery or it can be reuse, recycled, and remanufactured for other secondary purposes. At the same time, system thinking is crucial for renovation projects,

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as designing out waste and closing the loops needs holistic thinking regarding renovation measures (Ellen MacArthur Foundation, 2017; McKinsey et al., 2015). For example, selective dismantling verses deliberate collapse strategies would impact the re-looping of construction and demolition waste and facilitate closed-loop or open-loop system boundaries. As circularity in construction industry is fragmented and mainly focused on material reuse and waste management, it is hard to validate the interventions made to achieve circularity (Benachio et al., 2020; Charef et al., 2022; Charef & Lu, 2021; De Pascale et al., 2021; Rahla et al., 2019, 2021)

Diverse variety of C-indicators – 'a measuring tool that aims to quantify the performance and progress of systems from CE perspective' (Saidani & Kim, 2022); are complemented with LCA methodology to know the environmental impact along with resource efficiency (Braakman et al., 2020; Gillott et al., 2023). Authors, Lucia. R and Eliana. M (2021) define circularity as a multifaceted concept, that generates difference interpretations (Rigamonti & Mancini, 2021); while M. Saidani et al (2019) highlights the relative usage of C-indicators, calling them 'relative device' (Saidani et al., 2019). At the same time, as CE aligns to sustainable development goals (SDGs), there is a need to explore a combination methodology which specifically accounts for sustainability impacts of circular strategies has been stress by European Union and researchers (de Oliveira et al., 2021; Khadim et al., 2022; Nugent et al., 2022), which explores the connection between whole lifecycle thinking and circular economy. Thus, this study critically evaluates C-indicators to understand the nexus between these assessment methodologies, highlighting their ideological similarities and differences. This study can act as a steppingstone to develop an up-to-date, empirical, and accurate circularity assessment method or tool or framework for existing building stocks.

2 Methodology:

The following sections describes the complementary approach followed for critical analysis in the next section.

2.1 Systematic Literature Review of methodological approaches:

Consistently developed C-indicators have resulted in many variations, which have given relative importance to building layers, reverse logistics, modularity, flexibility, durability, recyclability, reusability, recovery, remanufacturing, financial aspects, sustainability principles, etc., that we have to ask, what exactly are we measuring. A systematic literature review targeted the peer-reviewed article indexed in SCOPUS and Web of Science, where with systematic approach the highly cited articles were selected for further analysis. Following string (("circularity indicators" OR "indices" OR "measures") IN "construction industry") was used for selecting the articles. With the review of 55 articles, it is observed that there are more than 50 different C-indicators adopted by researchers and are available commercially. At the same time, 38 different methods are found to be appropriate for use in construction industry, content analysis of these articles helped in framing of the design research concept based on system thinking approach for renovation projects.

2.2 Design research concept:

The system thinking approach helps to develop a decision-making framework that encourages thorough evaluation of inherent relationships between the interacting, interrelated or interdependent parts that form a complex and unified whole (Davidson & Venning, 2011; McDonough & Braungart, 2002). An individual building acts as a holistic system at a meso scale, where assessment of renovation project needs to be performed at three systemic levels, i.e., materials, products, and building. Review focused on distinguished aspects of methodological applicability and ideological bases which highlighted the links between various systemic levels to assess circularity of system (building) and their alignment to sustainability, i.e., environmental, economic, and social. Especially, for renovation projects the system thinking approach is primarily dependent on reverse logistic of the building layers in terms of appropriate design for deconstruction (DfDx) mechanism, which eventually impact the scope of reusability, recyclability, recovery, and disposal (Dams et al., 2021; Kanters, 2020). Thus, there exists a complementary connection between (i) brand's shearing layers and (ii) design for deconstruction mechanism, which influences (iii) R-frameworks promoted by waste hierarchy principle (European Union, 2018). The R-frameworks significantly influences the (iv) re-looping cycles integrated between biological or technical cycles as per cradle-to-cradle paradigm. The collaboration of these factors impacts the environmental efficiency and resource efficiency which highlights the link between (v) sustainability pillars and circular strategies. Although LCA assessment and C-indicators are primarily based on the quantitative calculation approach, it came to light that majority of the indicators consider semi-quantitative (vi) calculation approach to account the disassembly, adaptability, modularity, durability, and flexibility of the buildings. Moreover, (vii) financial aspects govern the final decision-making by the stakeholders as energy renovation measures are less preferred compared to aesthetic renovations which are accounted by the means of life cycle cost analysis (LCCA). These systemic level integrations were classified into seven aspects with two to four key performance indicators (KPI's) for further evaluation of ten selected C-indicators. Details regarding each KPI's are summarized in table 1 below.

TABLE I. Definitions of aspects and KPI's relevant for systemic level thinking

Aspects and KPI's	Description of the term Authors
Brands Layers	The shearing layers, consisting of seven differently paced systems, i.e., Site, Structure, Skin, Services, Space Plan and Stuff have different lifecycle duration, which has specific characteristics that impact the recyclability of these components and elements (Brand, 1995; R. J. Geldermans, 2016; R. Geraedts, 2016; R. P. Geraedts & Prins, 2016; Gillott et al., 2023; Sala Benites et al., 2022).
Re-loop cycles	Cradle to cradle (C2C) approach which creates regenerative designs and follows a cyclical approach of mimicking nature's system thinking of waste is food, and resources are constantly reused (Cole et al., 2013; McDonough & Braungart, 2002). **Biological cycles** are in interconnected and interdependent on the complex web of natural systems on Earth. These are biodegradable materials (Capra, 1997; Reed, 2007; Sala Benites et al., 2022). **Technological cycles** are connected to processes and systems attached to the value chain and requires responsible technological management solutions for disposal and recycling (R. J. Geldermans, 2016; Shahbazi et al., 2020).
WFD R-framework	The 4R-framework – reduce, reuse, recycle and recover as formulated in the waste framework directive which highlights the importance of waste management practices within European Union (European Union, 2018; Sihvonen & Ritola, 2015; Zhang et al., 2022) **Reduce** waste and promoting sustainable consumptions with good waste management and resource re-optimization. **Reuse** products, components, and materials for their original purpose without further processing for refurbishment. **Recycle** with an intention to retain or recover the valuable resources in order to repurpose them in new products. **Recover** the material at the end-of-life scenario with energy recovery i.e., waste to energy processes and other disposal of materials. Also enable traceability of the material at disposal with advanced technology
Reverse Logistics – Design for deconstruction (DfX)	A process which enables reduction of waste with appropriate sorting with an aim to return, repair, remanufacture, recycle and proper disposal. For the buildings design for deconstruction (DfX) aims to reduce waste with facilitating collaboration amongst stakeholders to ensure re-looping flows throughout the material lifecycle (Dams et al., 2021; L. C. M. Eberhardt et al., 2022; Escaleira et al., 2019; B. Geldermans & Rosen Jacobson, 2015; R. J. Geldermans, 2016; Munaro & Tavares, 2023; Rasmussen et al., 2019; Sanchez et al., 2021). **Disassembly -** the process of taking apart the building's components, elements, and materials by retaining the value preposition and can be re-looped into the value chain, with repair, maintenance, recycling, refurbishments, remanufacturing, or disposal. **Adaptability -** the ability of system (building) to adjust, modify or change as per the changing circumstances. This integrates flexibility, durability and open to change aspects with respect to the dynamic needs of time. **Modularity -** The building elements and components would be designed such that the modules are self-contained units and can be easily replicated, combined, replaced and interchangeable. A typical module can be assembled or connected to form a complex system (building). **Longevity -** The length of the time that various components, elements, and materials within the system (building) remains in use. It highlights the extended lifespan and duration of various shearing layers of the building.
Sustainability Pillars	Also known as the pillars of sustainability that refer to the three interconnected dimensions of sustainability (Lei et al., 2021; McDonough & Braungart, 2013; Saidani et al., 2017, 2019, 2022; Saidani & Kim, 2022; Sparrevik et al., 2021). **Social** dimension emphasizes the quality of life, health and well-being of citizens promoting social sustenance. **Economic** dimension involves creating prosperous economies promoting social equity and environmental growth. **Environmental** dimension involves the holistic approach of maintaining the ecological balance of the planet.
Calculation approach	C-indicators are based on accounting of materials reusability, recyclability, and recovery, which can be absolute or relative considering the objective and subjective aspects of materials (Androsevic et al., 2019; Saidani & Kim, 2022; Verberne, 2016). **Quantitative –** the objective aspects of materials, such as mass, volume, density, environmental impacts, etc. **Semi-quantitative** – combines the objective and subjective aspects of materials based on expert evaluation. **Qualitative** – the subjective aspects of materials, such as reuse potential on expert evaluations.
Financial aspects	Financials decisions are significantly important as stakeholders are influenced by the aesthetic purposes over energy improvement measures and resource efficiency (Azcarate-Aguerre et al., 2022; Braakman et al., 2020; Cottafava & Ritzen, 2021; Donatello & Dodd, 2021; Rasmussen et al., 2019).

3 Critical analysis

Based on their relevance of use in renovation projects, ten distinguished C-indicators were further grouped in LoC based tools, LCA and LCC integrated tools, and BIM integrated commercial tools. The empirical data analysis shows the varying degree of inclusions of various aspects in these C-indicators (see table 2 below), such as C-indicators which employ quantitative approach account for R-framework KPI's, while semi-quantitative approach account for reverse logistics KPI's. At the same time, biological cycles and social KPI's are not accounted for in majority indicators.

TABLE II. Details of KPI's covered in C-indicators

Governing factors of circularity / **C-Indicators, Authors, and year**	**Brands layers**	**Re-loop cycles**		**WFD R-frameworks**				**Reverse Logistics - Design for Deconstruction (DfDx)**				**Sustainability Pillars**			**Calculation approach**			**Financial aspect**
		Biological	Technical	Reduce	Reuse	Recycle	Recovery	Disassembly	Adaptability	Modularity	Longevity	Social	Economic	Environmental	Quantitative	Semi-quantitative	Qualitative	
Level of Circularity (LoC) based indicators																		
MCI (EMF & Granta Design, 2019)			x	x	x	x									x			
FLEX (Ver. 1.0 to 4.0) (B. Geldermans & Rosen Jacobson, 2015)	x				x	x		x	x	x	x					x	x	
BCI (Verberne, 2016)	x		x	x	x	x		x							x	x		
LCA and LCC integrated indicators																		
Level (s) (Donatello & Dodd, 2021)	x		x		x	x	x	x	x	x	x		x	x		x	x	x
MBCI (Braakman et al., 2020)		x	x			x		x	x				x			x		x
PBCI (Cottafava & Ritzen, 2021)			x	x	x	x		x						x	x	x		x
REGENERATE (Gillott et al., 2023)	x		x		x	x	x	x	x	x	x			x		x	x	
BIM integrated commercial tools																		
FCB (Kubbinga et al., 2018)		x	x		x			x	x					x		x	x	
MAD-CI (Madaster, 2021)	x		x		x	x	x	x	x		x		x	x		x	x	x
One Click LCA (One Click LCA, 2021)	x	x	x		x	x		x	x	x	x		x	x		x		x

3.1 Relationship between C-indicators

The following section critically evaluates the strengths, limitations, and areas of improvements (Table 3). In practice, decision making for selecting specific C-indicator could be challenging, as trade-offs are present while prioritizing resource efficiency and environmental impacts.

4 Results

Fundamentally, these C-indicators have conditional, beneficial and trade-off relationships while accounting for sustainability impacts of circular strategies.

4.1 Beneficial relationship between C-indicators

The base indicators such as MCI, BCI and FLEX which were developed during the initially period, measure the circularity in hierarchical sequence of the system (building) (EMF & Granta Design, 2019; R. Geraedts, 2016; Verberne, 2016). Although these are too dependent on the mass of product, these are used for further enhancement of methods rather than creating new methodology or frameworks due to their simple and accurate calculation of the recirculatory flows (Cottafava &

Ritzen, 2021). Although based on quantitative approach they fail to measure sustainability aspects, which are overcomed by the LCA and LCC integrated indicators. Moreover, the supply chain of material procurement and recirculation to the secondary markets in not included in these methods. At the same time, these C-indicators are integrated with the BIM based C-indicators showing their applicability in the commercially available tools, such as FCB, MAD-CI and OneClick LCA. These BIM based tools integrate numerous frameworks like, BREEAM, LEED, FLEX, DGNB, EPD's, etc., with additional KPI's such as flexibility score and disassembly index. Moreover, these tools act as a quick way of scrutinizing the environmental and resource efficiency of the building projects with the help of material passports integrated in these tools (Honic et al., 2021), yet they lack context specific social dimension for sustainability assessment (Table 2 and 3).

TABLE III. Strengths, limitation and areas of Improvement for C-indicators

C-indicators	Strengths	Limitations	Areas of Improvements
LoC based indicators	**- Can be used as base indicators to propose new tools and methods. - Micro level accuracy. - Supports data in form of bill of materials and bill of quantities.**	**- Too dependent on the mass of products and material flows of recirculated products are unaccounted. - Sustainability environemental impacts are unaccounted in the calcualtion.**	**- Can integrate the financial aspects with Brand's layers and LCA methodology. - Accurate auditing of materials**
MCI	S1. Precisely designed for product level assessment. S2. Supports data in form of bill of materials and bill of quantities.	L1. Too dependent on the mass of product and material flows of recirculated products unaccounted. L2.DfDx approaches unaccounted	Can complement the LCA assessment to know the environmental impact.
FLEX	S1. Integrated the necessary DfDx approaches, i.e. flexibility and adaptability along with Brand's shearing layers. S2. Tested on renovation projects classifying use (U) dynamics and transformation (T) dynamics	L1. Too dependent on subjective weighing method of qualitative assessment of materials, so chances of bias are high. L2. Sustainability impacts unaccounted. L3. Use of bill of materials (BOM)	Can integrate other aspects of DfDx approaches, life longetivity, modularity and disassembly. Financail aspects can be added.
BCI	S1. Precisely designed for system level for building scale	L1. Not integrated with Brand's shearing layers and sustainablity impacts.	Can complement the LCA assessment.
LCA and LCC based indicators	**-These align with the EU framework for CE. - LCA and LCC impacts combined with C-indicators. - Use of bill of materials (BOM)**	**- Circularity assessed by replacing standard components to circular components. - The labour and material cost are generic. - Use of bill of materials (BOM)**	**- Integration of on-site disessambly process with use of standard components. - Can integrate the challenges faced by labours and contractors on-site with financial aspect**
Level(s)	S1. EC proposed framework S2. Assess deconstruction potential for reuse, recyling and recovery.	L1. Dependent on BREEAM	Context specific alignment is needed.
MBCI	S1. Integrates LCC with BCI S2. Method doubles circularity without increase in cost.	L1. DfDx approaches are unaccounted for and uses generic labour and material costs.	Integrate with Brands layers with context specific labour and material costs
PBCI	S1. Complements EE and EC with BCI and provides single score for entire building	L1. Generic system boundaries L2. Approximation in disassembly processes	Accurate system boundaries with inclusion of disassembly process
REGENERATE	S1. Through tool that integrates EC and C-indicators with Brand's layers.	L1. Design for Greater London Authority (GLA), so city zones are designed for GLA. L2. Financial aspects	Contextual modification possible which standard replacement strategies. Add financial aspects with LCCA.
BIM integrated tools	**- Rich database for commencing analysis in initial stage of project.**	**- The KPIs are dependent on sustainability aspects, but LCA impacts are complemented and not integrated. - Not an open-source database.**	**- Can integrate DfDx approaches into a comprehensive approach. - Can integrate multiple-cycle with appropriate LCIAtable**
FCB	S1. Credit base approach	L1. Dependent on sustainability related KPIs	Can integrate DfDx approaches
MAD-CI	S1. Rich databank of EPDs along with dissassembly index and functional lifetime.	L1. Not an open-source database as well as nordic database is absent.	Context specific material bank can be upgraded for use in research and academia.
OneClick LCA	S1. Various frameworks and standards are integrated for assessment	L1. Not an open-source database	Can integrate multiple-cycle with appropriate impact allocation.

4.2 Conditional and trade-off relationship between C-indicators

Lifecycle assessment (LCA) is used as a standardized assessment methodology to calculate the sustainability of system (building) (Swedish Standards Institute, 2006). Based on ISO 14040/44 it quantifies environmental impacts of products, materials, and system throughout their lifecycle, which has emerged as the most promising approach to achieve circularity (Rigamonti and Mancini 2021). LCA provides a much needed consistent and robust methodology which accounts for relevant resources and impact categories thus providing holistic perspective of social and economic benefits besides environmental impacts (Rigamonti & Mancini, 2021; Saidani & Kim, 2022)

Attempts made by researchers with frameworks like Level(s) (Donatello & Dodd, 2021) and REGENERATE (Gillott et al., 2023), and methodologies like predictive building circularity indicator (PBCI) (Cottafava & Ritzen, 2021) and modified building circularity indicator (MBCI) (Braakman et al., 2020) ascertain the conditional and trade-off relationship of complementing embodied energy (EE), embodied carbon (EC) and lifecycle cost analysis (LCCA) with the base C-indicators (Table 2 and 3). Cottafava and Ritzen (2020) found that coupling embodied energy (EE) and embodied carbon (EC) with corresponding C-indicators can provide a single score for the entire building instead of mass, volume, and economic value. However, they argue accurate evaluation of the disassembly process in renovation projects with strict system boundaries is crucial, as contextual parameters impact reusability, recyclability, EE, and EC (Cottafava & Ritzen, 2021). While Braakman et al. (2021), emphasize the importance of economic feasibility as an indicator of circularity, suggesting that relying less on product mass and more on LCC while substituting virgin materials with recycled and biological ones can double circularity without increasing costs (Braakman et al., 2020). The recently developed tool, REGENERATE, incorporates DfDx approaches, circular material selection, and resource efficiency through 86 criteria, integrating brand's shearing layers. It promotes material level circularity by accounting material quantity in terms of recycling and waste data, which uses bill of materials with corresponding EC values based on materials intensity (Gillott et al., 2023). Similarly, Danish study of subsequent reuse of building components and elements in other buildings demonstrate considerable reduction of embodied emissions with upcycling and design for disassembly techniques (Rasmussen et al., 2019), however the allocation of impacts for production and end-of-life are debatable in accounting circularity of building materials (Lei et al., 2021).

5 Current research gaps

While progress has been made in developing C-indicators into a comprehensive framework, the multi-cycling of materials, i.e., multifunctionality and multiple reuses is overlooked in these. Moreover, other study which used LCA methodology for assessing circularity highlight the challenges faced in assigning lifecycle impact allocation within the selected system (building, façade, window, etc,.) due to the multiple reuses of building materials, which may lead to double accounting and burden shifting (Azcarate-Aguerre et al., 2022; L. Eberhardt et al., 2019; L. C. M. Eberhardt et al., 2022; Sigüenza et al., 2021; Van Gulck et al., 2022).

6 Discussion and way forward

A comprehensive methodology which considers whole life carbon thinking promoted by EU has been investigated by numerous authors. In this study, 18 KPIs of seven aspects are classified and summarized in table 1. These aspects are used to analyze ten C-indicators relevant for the existing buildings. As they promote new frameworks and methodology, as summarized in Table 2 and 3, these approaches have several limitations, including (i) they are too dependent on the mass of the material, (ii) unaccounted recirculation of materials, (iii) lack of discussion on integration with LCA and (iv) lack of integration with actual labor and material cost. In fact, these tools mainly focused on improving the base C-indicators, such as MCI and BCI with inclusion of brands shearing layers and design for deconstruction approaches. At the same time, they advocate to study the implication of the disassembly process in renovation project with strict system boundaries as contextual parameters may impact the multiple-cycles, thus impacting the environmental impact as well as circularity scores. Moreover, further study needs to focus on the dynamic aspects of impact allocation in LCA methodology while accounting for the recirculation of the building materials to understand the impacts of burden shifting. With this background further research needs to formulate practical guidance and frameworks with observing the current system dynamics of the construction industry, as innovative circular business models facilitate the holistic recirculation of the materials within the linear value chain. The approach needs to expand the system boundaries from the micro systemic level to meso and macro level as the materials transition impacts the circularity scores.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

All authors contributed to the study conception and design. Data collection, material preparation and analysis were performed by [RA]. The first draft of the manuscript was written by [RA] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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