





Development of Circularity Assessment Indices for Construction Sector: A Critical Review

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Abstract. The efficient assessment of circularity in buildings requires a comprehensive consideration of diverse elements such as material selection, design principles, construction methods, operational effectiveness, and end-of-life management. However, the absence of a consistent methodology poses a significant challenge in circularity assessment, as extant evaluation techniques either offer a broad perspective on circularity or concentrate on specific components. The lack of clarity in the variations and ranges of circularity indicators further hampers the ability to thoroughly evaluate a building's performance, leading to a preference for a qualitative approach. This study aims to overcome the challenges associated with the development of circularity assessment indices by proposing a generic framework for index generation, providing guidance to tool developers and decision-makers in understanding the rationale behind circularity indices within the building environment literature. To achieve this goal, the study conducts a literature review elucidating common methods employed in developing circularity indicators and indices as well as the aggregation methods encompassing both qualitative and quantitative indicators, emphasizing how their weights are determined and utilized in the aggregation process. This critical review offers insights into current practices, identifies challenges, and fosters a deeper understanding of the inherent complexities in circularity assessment. Ultimately, this study contributes to the advancement of methodologies for evaluating and enhancing circularity in building, addressing a vital aspect of sustainable construction practices.

Keywords: Circularity Assessment · Circularity Indicators · Circularity Index Generation · Construction Sector

1 Introduction

The imperative for stakeholders to deliberate on strategies for ensuring their buildings cater to their requirements while aligning with sustainable and environmentally friendly concepts—such as green building, zero energy, carbon neutrality, and the circular economy (CE)—is steadily increasing. The CE represents an economic model that aims to eliminate

waste production and foster the perpetual use of resources by creating closed-loop systems. Within the building sector, employing CE principles is at the top of environmental and sustainable development agendas, given the sector's high footprint and elevated consumption of resources. CE principles can be seamlessly applied throughout all life cycle stages, particularly in building design, construction, operation, and end-of-life management, to minimize waste, reduce carbon emissions, and enhance the circularity value of materials and products used. By embracing the tenets of the CE, the building sector emerges as a pivotal contributor to the realization of a more sustainable and resilient future.

To ensure that buildings in the construction industry align with CE concepts, it is imperative to employ robust criteria and indicators grounded in established standards [1], insight from stakeholders [2], and established practices [3]. This approach guarantees comprehensiveness and high-quality assessments. The criteria and requirements established by the CE should be translated into the use of various metrics or indicators to measure a building's performance and its impact on the environment and human health [1–3]. Through the application of such metrics and indicators, stakeholders can identify areas requiring improvement, maintain consistency and quality over time, and optimize their use of time and resources.

Several circularity tools, methods, frameworks, and indexing systems have been created based on such standards and metrics. Examples include the Whole-Building Circularity Indicator (WBCI) [1], the Building Circularity Indicator (BCI) and its derivatives [4], as well as HOUSEFUL's Building Circularity Methodology (BCM) [5]. These tools enable stakeholders to make well-informed decisions based on high-quality standards and predetermined criteria. Moreover, they provide opportunities to retain the value of projects and potentially elevate them to higher standards owing to their superior quality and services that support sustainability, ecology, and human health [3].

However, the assessment of circularity faces numerous challenges, with one significant issue being the establishment of transparent criteria for quality [1]. The lack of clearly defined and easily understandable criteria hampers the promotion of sustainable and environmentally friendly concepts within the building sector. Typically, current indices for building construction focus on specific goals or aspects of circularity, such as minimizing the use of new materials and closing the waste loop. However, focusing solely on individual aspects can impact other facets and, therefore, overall circularity levels, leading to incomplete and non-comprehensive results. Another obstacle is the varied understanding and appreciation of circularity strategies among stakeholders. End-users, for instance, may perceive the incorporation of recycled or secondary materials as a compromise in the building's quality. This underscores the necessity of considering additional criteria that can effectively communicate the added values and benefits of implementing CE practices to a wider range of stakeholders along the value chain. Another example of the challenges is that available tools, while effective in providing synthetic data for decision-making and production management, often fall short of facilitating meaningful communication of information to stakeholders. Karaca et al. argue that while measurable criteria are generally preferred in developing indices, the scoring may be criticized due to differences in stakeholder opinions. To address this, they

recommend using different weights for various perspectives, allowing for a customized approach to criteria [2].

This research aims to critically address the abovementioned gaps by reviewing the processes and steps involved in developing circularity assessment indices for buildings. It presents a review of how common circularity indices are developed or generated. Additionally, it discusses their aggregation methods, considering both qualitative and quantitative indicators, focusing on how weights are identified and used in the aggregation process. Ultimately, the research aims to guide tool developers and decision-makers in the academic and sectoral areas by providing them with a step-by-step generic index generation framework.

2 Circularity Assessment Frameworks

Implementing CE in the construction sector poses a significant challenge, primarily due to the absence of standardized assessment indicators. This dearth hampers the ability to effectively measure the impact of CE initiatives and compare their success across relevant industries and regions. To address this challenge, it is necessary to consolidate the most common assessment criteria and indicators into a unified approach covering all CE requirements and ensuring transparency and comprehensiveness in addressing CE strategies and principles. Therefore, establishing frameworks with a consistent methodology is critical for assessing circularity within building processes.

In this section, two frameworks were selected based on their wide-ranging applicability in the field. The chosen frameworks underwent thorough analysis to gauge their effectiveness in assessing the circularity of building materials and construction processes. Each assessment framework provides a measurable methodology for evaluating the effectiveness of resource management, reuse, and recycling in the building sector.

The first example is the Circular Construction Evaluation Framework (CCEF) proposed by Dams et al. (2021) [6]. CCEF is a noteworthy example of circularity assessment as it is based on international design code guidelines and critical literature analysis to develop assessment considerations for the selection of circularity criteria. CCEF is a versatile framework applicable to both existing buildings and newly proposed projects and can be used by diverse stakeholders involved in project development. The methodological approach of CCEF involves quantifying the level of circularity within the examined project with respect to several relevant criteria. This assessment occurs at two distinct levels: the whole-building level and the building element level. Qualitative and quantitative evaluations are employed to score circularity credentials for criteria at each level. In a whole-building assessment, 14 criteria are employed and categorized into four groups: 1) recorded information design, data, and materials; 2) adaptability in design; 3) simplicity in design; and 4) health and safety. At the element level of assessment, 14 criteria are delineated and grouped under durability, material inventory, and finishes. Additionally, three individual criteria lack a higher categorization but are integral to the assessment: reversibility of connections, reusability percentage, and recyclability percentage. The structured organization of criteria into larger groups facilitates a comprehensive evaluation of circularity across different dimensions of construction projects.

The second framework, the Disassembly and Deconstruction Analytics System (D-DAS), is designed to seamlessly integrate end-of-life performance evaluation and consideration into the design stage and process of buildings to optimize their circularity [7]. The system's main goal revolves around selecting materials, relying on incorporating the principles of Design for Disassembly (DfD). This approach not only facilitates efficient material use and recovery but also significantly reduces waste in the built environment at the end of a building's lifecycle. Building information modeling (BIM) is used and expanded upon by D-DAS to develop a four-layer system architecture. These layers collaborate harmoniously to create a unified system. The data used in the calculations are drawn from building design (parametric building models, materials), building material specification (material properties and status), and deconstruction and demolition information (historical data). To execute its functionalities, the framework employs a Revit plug-in, enabling it to perform three essential operations to optimize and assess certain circular aspects of the project.

3 Circularity Indicators

Circularity is evaluated through a range of circularity indicators or a specific metric that uses single or aggregated scores [4]. Circularity metrics are commonly employed to measure the impacts or benefits generated by circularity strategies. In resource efficiency and sustainability performance (covering environmental, economic, and social aspects), there has been a proliferation of indices and frameworks, contributing to an excess of indicators [1]. In consideration of the aforementioned points regarding circularity metrics, this section refines its focus to analyse indicators related to both material and building circularity, emphasizing three key areas: (1) laying the groundwork for circularity metrics used thus far, (2) assessing the validity of current circularity metrics based on predefined requirements and a CE definition anchored in the sustainability concept, and (3) offering guidance and recommendations on how to generate circularity metrics.

Unlike most products in the manufacturing industry, buildings possess extended service lives, incorporate diverse materials, involve multiple stakeholders, and are highly customized and context-dependent. These distinctive characteristics make it challenging to implement standardized circularity indicators in the building sector [1]. Using reliable indicators becomes critical when assessing progress toward the CE. Given the fundamental purpose of a circularity indicator, which is to objectively assess critical aspects and dimensions of CE in construction and built environments, the majority of existing circularity indicators employ quantitative measures. However, indicators can be quantified or qualified based on observations, measurements, calculations, or a combination of complex methods. Focusing on these objectives sheds light on the specifics of the *Material Circularity Indicator (MCI)* and its adaptation to the building context, considering complementary design aspects to generate the *Building Circularity Indicator (BCI)* and its derivatives. Additionally, attention is given to *HOUSEFUL's Building Circularity Methodology (BCM)*. These selected indicators are evaluated below to provide a comprehensive methodology perspective for circularity assessment.

The Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation in 2015, stands out as a sophisticated metric designed to gauge the circularity of industrial materials and products [8]. Unlike simpler indicators, the MCI provides a comprehensive evaluation of a product's circularity by emphasizing the maximization of material restoration within its components.

Comprising three key product characteristics, the MCI focuses on the amount of virgin raw materials (V) attributed to the product, the amount of unrecoverable waste (W) associated with the product, and the utility factor (X), which accounts for the product's lifetime. Calculation of the MCI involves considering the proportion of material input (virgin or non-virgin), material output (energy recovery or landfill disposal), and the technical lifecycle of a product. Together, these factors represent the theoretical circular capacity of each product. In the context of buildings, a Bill of Materials (BOM) is used to calculate the MCI for individual products.

What sets the MCI apart is its adoption of a multidimensional assessment methodology, taking into account various factors. Its primary input involves a thorough investigation into the proportion of resources sourced from both virgin and recycled materials, as well as components repurposed from previous usage. In addition, the MCI considers the utility gained from using the product by comparing the duration and intensity of product consumption to industry norms for similar product types. To calculate the MCI of a product, the Linear Flow Index (LFI) and the factor $F(X)$ are employed. The factor $F(X)$ is formulated as a function F of the utility X , determining how the utility of a product affects its MCI [8].

The MCI is used within the built environment context to formulate the Building Circularity Indicator (BCI) [4]. The BCI calculation adopts a bottom-up approach, employing a hierarchical methodology that diverges from relying on the calculation and aggregation scores of different criteria. Instead, it uses a progressive calculation involving four indicators. This process begins with the MCI and advances through the Product Circularity Indicator (PCI), followed by the System Circularity Indicator (SCI), culminating in the overall Building Circularity Indicator (BCI). The overarching concept of the BCI is to scrutinize input, usage, and output. The development methodology of the BCI complements the original MCI model for subsequent indicator calculations with design criteria rooted in an extensive list of KPIs. These KPIs are derived from expert semi-structured interviews, followed by the scholar's subjective prioritization to streamline the list. The result is a selection of the most crucial circularity indicators, subsequently validated by an expert panel. This comprehensive process yields a conceptual framework translated into an assessment methodology, which is then tested and validated through a case study using Excel functionality. The circularity indicators exclusively encompass technical requirements, comprising two components: (1) material specifications and (2) design for disassembly (functional, technical, and physical). Verberne's BCI marks the pioneering effort in establishing whole building circularity indicators, laying the foundation for subsequent BCIs and other building circularity models. These later models build upon the initial BCI, addressing some of its limitations.

The last examined indicator originates from the Horizon 2020 HOUSEFUL project (2018–2022), which specifically addresses “Innovative circular solutions and services for new business opportunities in the EU housing sector”. The HOUSEFUL project introduces a global circularity indicator known as the Building Circularity Score (BCS) [6]. The novel indicator employs a methodology designed to evaluate circularity at the initial stages of housing design, encompassing new constructions and retrofits. The HOUSEFUL approach is fundamental in determining circularity levels, relying on six key pillars: energy, water, material balances, social and environmental impacts, and life cycle cost reduction. Operating under a life-cycle-based methodological approach, the BCS aligns with established building sustainability standards and practices, such as those endorsed by the CEN Technical Committee 350 (CEN TC 350) and the European Union (EU) LEVEL(s). Notably, the BCS offers the potential to enhance water and energy circularity across various life cycle stages.

4 Index Aggregation Techniques

In general, criteria and indicators play a critical role in indicating the direction of change over time and across various units. They also serve as valuable instruments for establishing policy priorities, benchmarking, and performance monitoring. When disparate indicators are amalgamated into a single index (referred to as a ranking, method, or tool) based on an underlying model, the resultant composite is termed an “index” or aggregated indicator [9]. While it is acknowledged that science cannot provide an entirely objective approach to creating a definitive index that encapsulates a complex system, it can significantly enhance the robustness and transparency of aggregation processes. Consequently, this section provides aggregators and tool developers with a generic index generation framework (Fig. 1) as a checklist for constructing an index, encompassing a generic framework for index generation steps and methodology. The index creation process begins with the establishment of a solid theoretical framework. The framework should explicitly identify the phenomenon under assessment, its constituent parts, distinct indicators, and weights reflecting the relative importance of these components and the dimensions in the final composite. Emphasis should be placed on measuring what is desirable rather than solely relying on readily available indicators.

Variables should be selected based on their applicability, analytical quality, timeliness, and accessibility. The potential hindrance of missing data to the development of reliable indices is acknowledged, and a well-managed step for the imputation of missing data should be incorporated in such situations. The uncertainty associated with imputed data must be considered when estimating variance.

An increasing number of decision-makers find themselves tasked with developing aggregated indicators in contemporary settings. Unfortunately, many of these indicators are often selected arbitrarily, lacking thoughtful consideration regarding their potential interactions with other indicators.

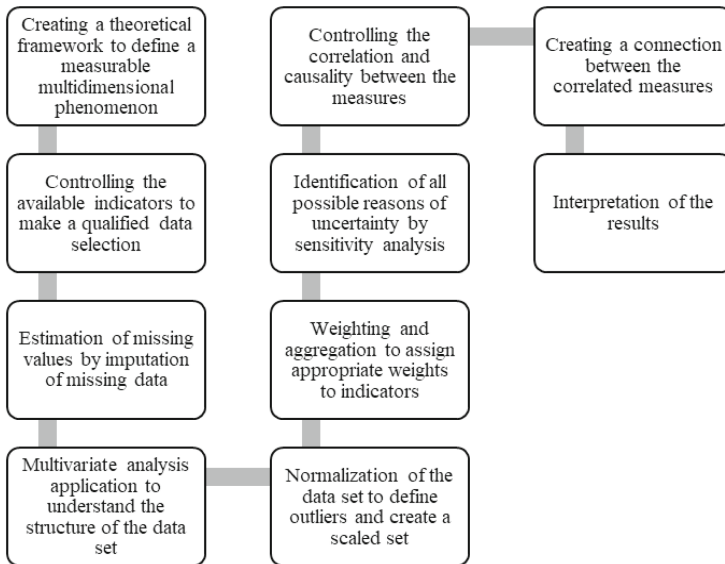


Fig. 1. A generic structure of index generation steps (Source: own elaboration).

Consequently, the applicability of the dataset can be effectively assessed through Multivariate Analysis (MVA), which not only facilitates comprehension of how methodological choices impact results but also serves as a valuable tool in this context. Among the prevalent MVA methods are Multiple Linear Regression Analysis, Principal Components and Factor Analysis, Cronbach Coefficient Alpha, and Cluster Analysis, as outlined in Table 1.

Before calculating an index, it is imperative to normalize the sub-indicators measured in different units, a crucial technique preceding any data aggregation. This “normalization” process is essential due to the common occurrence of diverse measurement units among indicators in a dataset. Furthermore, a challenging aspect involves determining appropriate weights [10]. This issue is closely tied to the implicit importance of attributes, as exemplified by the ‘trade-off’ between pairs of criteria during the aggregation process [11]. Consequently, this study delves into the literature with a particular emphasis on methods for generating indices, specifically focusing on weighting and aggregation. Table 2 outlines the commonly cited methods in this field, providing a comprehensive overview.

Table 1. A short table of Multivariate Analysis Methods (MVAs)

MVA Methods	Specifications	Mathematical Formulation	Explanations
Multiple Linear Regression	Handling a large number of variables of different types	$\hat{Y} = \alpha + b_1X_1 + \dots + b_nX_n$	\hat{Y} is an indicator $b_1 \dots b_n$ are the regression coefficients (weights) X_1, X_2, \dots, X_n are sub-indicators
Principal Components and Factor Analysis	Assessing statistical characteristics in the data with a lack of correlation	$Z_j = \sum_{i=1}^p a_{ij}X_i$	X_1, X_2, \dots, X_p are variables Z_1, Z_2, \dots, Z_p are principal components
Cronbach Coefficient Alpha	Utilizing a coefficient of dependability which allows for assessing the strength of correlations between a group of sub-indicators	$\alpha = \frac{p\bar{r}}{1+(p-1)\bar{r}}$	p is the number of indicators \bar{r} is an average intercorrelation among the indicators
K-means Clustering Analysis	Providing an alternative method for classifying variables and shedding some light on the data set's structure	$J = \sum_{j=1}^K \sum_{n \in S_j} X_n - \mu_j ^2$	n is the sample size k is number of clusters n is the examples to one of k clusters

Table 2. Weighting and Aggregation Methods Generating Indices

Normalisation Methods	Weighting Methods	Aggregation Methods
Ranking [9, 10]	Equal Weighting [11]	Compensatory Aggregation [8, 13, 14]
Distance to target [9, 10]	Budget Allocation Process [13]	Non-compensatory Aggregation [15–17]
Z-score [9, 10]	Analytic Hierarchy Process (AHP) [18]	Mazziotta–Pareto Index (MPI) [19]
Min-max [9, 10]	Conjoint Analysis (CA) [14, 20]	Penalty for a Bottleneck [21]
Proportionate [12, 22]	Correlation Analysis [14, 23]	Mean–Min Function [24]
	Multiple Linear Regression Analysis [25]	ZD Model [10]
	Principal Components and Factor Analysis [26, 27]	Directional Benefit-of-the-Doubt (BoD) [28]
	Data Envelopment Analysis (DEA) [29]	

5 Conclusion

A circular building aligns with the principles of the CE, emphasizing design, development, operation, and use in a manner that minimizes environmental impact and maximizes material circulation. The central objective within the construction sector is to diminish reliance on virgin materials, employing circular design strategies, efficient material characterization, and thoughtful material selection. Achieving this objective necessitates the adoption of a comprehensive circularity approach that facilitates the expression of ‘circularity indicators’ as quantifiable values. This approach is essential in reflecting the CE’s core tenet of optimizing the retention of value in materials and resources. In this regard, the current paper contributes by outlining the rationale behind circularity frameworks and indicators. It accomplishes this through a comprehensive review of two prominent frameworks and various widely-used indices in the literature, all aimed at quantifying circularity in buildings. The analysis of these tools provides valuable insights, enabling the formulation of a generic index generation framework. This framework serves as a guide for tool developers and construction industry professionals, offering a systematic overview of the circularity index generation process. It lays the necessary steps and requirements involved in generating circularity indices for buildings. Additionally, the paper sheds light on prevalent aggregation methods for indicators, offering clarity on the generation of a unified index.

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