Chapter 16
Circularity Tools and Frameworks for New Buildings

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Abstract The assessment of circularity in new building projects necessitates consideration of diverse factors such as material choice, design strategies, construction methods, operational efficiency, and end-of-life practices. Various tools and methodologies have been developed to aid stakeholders in the construction industry in evaluating these aspects and making informed decisions. With the dynamic evolution of the circular economy, understanding current circular practices is crucial for identifying areas needing enhancement. However, the absence of a tandardized approach poses a challenge, with existing methods often either too broad or narrowly focused on specific circular elements. This limits the comprehensive evaluation of system performance. Addressing these challenges requires practical tools, particularly for early

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design stages, that integrate quantitative methods to ensure circularity and environmental performance goals are met efficiently. This chapter reviews existing circularity assessment parameters, discusses aggregation methods for criteria and indicators, and evaluates available tools to guide researchers, practitioners, and policymakers in advancing circular practices in construction.

Keywords Building circularity · Circularity assessment · Circular economy · Construction industry

16.1 Introduction

The efficient circularity assessment of new buildings requires a multitude of factors that must be considered, including material selection, design strategies, construction techniques, operational efficiency, and end-of-life management. Consequently, a range of tools and methodologies have been developed to evaluate these aspects and support decision-making processes for stakeholders involved in the construction industry (CI).

With the dynamic evolution of the circular economy (CE) within the sector, it is imperative to acquire a comprehensive understanding of the circular practices that have been introduced. This understanding is crucial for distinguishing the current state of implementation and identifying areas that require further application or improvement. Numerous review articles are available that identified existing tools and methods for circularity assessment in CI [10, 12, 18, 27, 30, 60, 70]. The current challenge of circularity assessment is the lack of a standardised approach. Previous assessment methods either focused on circularity as a general term or prioritised one specific circular element. A limited scope of circularity indicators restricts the comprehensive evaluation of the system's performance. Consequently, using individual indicators as the only means to assess the circular building design and disassembly potential remains challenging, along with quantitative support being the primary method.

While the theoretical foundations of circularity are well-established, which was also handled in various sections in this book, the CI requires more practical tools for assessing circularity. Particularly in the early design phase, there is a demand for quantitative methods and tools that facilitate circular designs, mitigating the risk of rework in later phases due to issues related to circularity and environmental performance. However, the main challenge remains in the availability of information for circular assessments within the current design workflow, where uncertainty and incompleteness prevail, especially in the BIM approach. To effectively guide the design workflow, there is a need for more automated circularity assessment tools capable of directly evaluating circularity aspects. Despite the development of frameworks, there is a perceived lack of supportive policies to improve the reuse and recycling in CI.

This chapter addresses the challenges and needs of circular assessment methods for new building projects. Readers may find other relevant details about the criteria, indicators, and implementation practices of such tools in the different chapters of the report. However, this chapter comprehensively reviews the circularity assessment parameters and their possible variations on indicators and factors, and then presents quantitative and qualitative aggregation methods for the criteria and indicators to develop guidelines, indexes, and rating methods. Finally, the available circularity assessment tools are evaluated as complete assessment methods. By examining the existing literature and drawing insights from case studies, this study intends to shed light on the diverse approaches researchers, practitioners, and policymakers employ in this rapidly evolving field.

16.2 Circularity Assessment Parameters: The Variation of Criteria and Indicators

The identification and use of criteria and indicators are key activities in circularity assessment. These activities have been the focus of much research in the field, and they are essential for developing effective circularity assessment methods. This subsection briefly overviews the criteria and indicators, typically the focal point of all the tools used in circularity assessment methods. It highlights the thematic and conceptual similarities and differences between the different criteria and indicators, which will help readers understand their relationships and key roles in the circularity assessment paradigm. For more detailed information, please refer to the dedicated chapters on the criteria and indicators of this book.

Circularity assessment is performed through the use of various circularity indicators or a specific metric that utilises single or aggregated scores [26]. However, the lack of consensus on the definition creates confusion in distinguishing a circularity indicator from other circularity metrics (e.g., index, framework). The lack of standardisation yielded the interchangeable use of multiple circular terminology, often hindering the result interpretation. The definition given by the Organisation for Economic Co-operation and Development (OECD) describes an indicator as "a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor" [74].

The use of generic circularity indicators is restricted by the unique attributes of CI. Unlike most products in the manufacturing industry, buildings have longer service lives, incorporate diverse materials, engage multiple stakeholders, and are highly customised and context dependent. These distinctive characteristics complicate the straightforward implementation of standardised circularity indicators in the construction sector [61]. A set of reliable indicators is vital when assessing the progress towards the CE [34]. This section reviews only those circularity metrics focusing on a single circularity aspect to be classified as a circularity indicator.

Numerous studies have reviewed existing circularity indicators [85]. reviewed a set of 55 circularity indicators and classified them into ten different categories, including CE implementation level (e.g., micro, meso, macro), loops (e.g., maintain, reuse/remain, recycle), performance (e.g., intrinsic, impacts), prospective (e.g., actual, potential), usages (e.g., improvement, benchmarking, communication), transversely (e.g., generic, sector-specific), dimension (e.g., single, multiple), units (e.g., quantitative, qualitative), format (e.g., web-based tool, Excel), and sources (e.g., academic, companies, agencies) categories. However, most of the reviewed indicators were adapted from existing methods in other sectors, specifically for the construction sector, with the exception of the Building Circularity Index (BCI).

Khadim [60] analysed another set of 24 specific circularity indicators with 35 variations with a wide scale of application (e.g., new and existing buildings, type of buildings, and scale of measurement). [77] reviewed common building construction and demolition waste (BCDW) indicators and classified them into four categories: process, government initiatives, market, investment, and platforms,industrial symbiosis; and sharing economy. Likewise, [55] discussed existing trends, challenges, and perspectives of CE in CI by reviewing existing indicators and their dimensions (e.g., environmental, economic, management/behaviour, technological, social, innovation, and policy). The existing circularity indicators reviewed in the literature are presented in Table 16.1. It is worth mentioning that not all indicators are thoroughly reviewed in the text.

16.3 Development and Design of Circularity Indicators

The majority of existing circularity indicators employ quantitative measures, given the fundamental purpose of a circularity indicator, which lies in the objective assessment of critical aspects and dimensions of CE in built environments. However, there are instances of adopting qualitative and semi-qualitative approaches in indicator development. For example, the measurement scale developed by [73] is a qualitative assessment scale that adopts selected indicators for the construction industry. Other examples of a semi-qualitative approach include C2C by Antwi-Afari et al. (2022) and the methodology described by [1]. Development of a new indicator can be challenging; therefore, adopting them from existing building assessment tools (e.g., BREEM, LEVEL(s), LCA, LCCA, MCI, BCI) remains a more popular approach rather than creating new indicators from scratch [57, 60]. The design of circular indicators can be reviewed on the examples of the most commonly used indicators. Indicators can be quantified or qualified based on observations, measurements, calculations, or a combination of complex methods. For example, the rate of virgin materials over reused materials in secondary materials used to construct new buildings is a simple or less complex indicator,it is simply a ratio.

The Material Circularity Indicator (MCI) is another example of a more complex indicator developed by the [37] to quantify the level of circularity for construction materials. It assesses the degree to which a product minimises linear resource consumption and maximises materials restoration within its components. Moreover, it evaluates the product's duration and intensity of use in comparison to an average

Table 16.1 Summary of the circularity metrics of the reviewed literature

The existing circularity indicators	References
Building Circularity Indicator (BCI)	[98]
Building Circularity Indicator (Disassembly Reconsidered) (BCIDR)	[96]
BIM-Based Building Circularity Assessment (BBCA)	[103]
Modified Alba Concept (For Foundations) (MAC)	[95]
Alba Concept BCI (ACBCI)	[8]
Modified Building Circularity Indicator (MBCI)	[19]
Predictive Building Circularity Indicator (PBCI)	[27]
Circularity Indicator for Pedestrian Bridges (CIPB)	[9]
ARCH Circular Environmental Indicator Framework (ARCHCEIF)	[42]
MADASTER Circularity Indicator (MAD-CI)	[67]
FLEX 4.0	[46]
Material Circularity Indicator (MCI)	[37]
Circular Economy Measurement Scale (CEMS)	[73]
Circular Economy Scale (CES)	[73])
Circular Business Model (CBM) Based Circularity Indicator (CBMCI)	[31]
Integrated Energy Performance and Circularity (IEPC)	[89]
BIM-based Whole-life Performance Estimator (BBWPE)	[6]
Bridge Circularity Assessment Framework (BCAF)	[25]
Synthetic Economic Environmental Indicator (SEEI)	[44]
Gypsum End of Life Measurement Indicator (GEOLMI)	[59]
RIPAT 1.0	[93]
Framework for Circular Buildings (FCB)	[63]
Platform CB’ 23 (PCB)	[21]
Circularity Calculator (CC)	[57]
Circular Building Assessment Prototype (CBAP)	[16]
C-CALC	[22]
Circulytics	[38]
Circular Assessment Criteria for Envelope (CACE)	[40]
Circular Construction Evaluation Framework (CCEF)	[29]
Material Reutilization Part (C2C)	[66]
Circle Assessment (CA)	[24]
Circularity Assessment Tool (CAT)	[80]
Circular Benefits Tool (CBT)	[4]
Circular Economy Company Assessment Criteria (CECAC)	[97]
Circular Economy Index (CEI)	[3]

(continued)

Table 16.1 (continued)

The existing circularity indicators	References
Circular Economy Indicators for India (CEII)	[90]
Circular Economy Indicator Prototype (CEIP)	[100]
Circular Economy Monitoring Framework (CEMF)	[36]
Circular Economy Performance Indicator (CEPI)	[56]
Circular Economy Toolkit (CET)	[3]
Circular Economy Toolbox US (CETUS)	[92]
Circular Economic Value (CEV)	[41]
Circularity Index (CI)	[56]
Circular Impacts Project EU (CIPEU)	[36]
Circularity Material Cycles (CIRC)	[79]
Closed Loop Calculator (CLC)	[43]
Circularity Pathfinder (CP)	[84]
Circularity Potential Indicator (CPI)	[3]
Super-efficiency Data Envelopment Analysis Model (DEA)	[103]
Evaluation of CE Development in Cities (ECEDC)	[17]
Evaluation Indicator System of Circular Economy (EISCE)	[3]
Indicators for Material input for CE in Europe (IMCEE)	[35]
End-of-Life Recycling Rates (EoL-RRs)	[37]
Environmental Protection Indicators (EPICE) in a context of CE	[75]
Evaluation of Regional Circular Economy (ERCE)	[22]
Eco-efficient Value Ratio (EVR)	[56]
Economy-Wide Material Flow Analysis (EWMFA)	[53]
Five Category Index Method (FCIM)	[65]
Hybrid LCA Model (HLCAM)	[45]
Indicators for Consumption for CE in Europe (ICCEE)	[35]
Circularity Indicator Project (ICT)	[99]
Indicators for Eco-design for CE in Europe (IECEE)	[35]
Indicators of Economic Circularity in France (IECF)	[68]
Integrative Evaluation on the Development of CE (IEDCE)	[83]
Input–Output Balance Sheet (IOBS)	[3]
Indicators for Production for CE in Europe (IPCEE)	[35]
Industrial Park Circular Economy Indicator System (IPCEIS)	Geng (2012)
Measuring Regional CE–Eco-Innovation (MRCEEI)	Smol (2017)
National Circular Economy Indicator System (NCEIS)	Geng (2012)
Product-Level Circularity Metric (PCM)	[3]
Regional Circular Economy Development Index (RCEDI)	[51]

(continued)

Table 16.1 (continued)

The existing circularity indicators	References
Resource Duration Indicator (RDI)	[3]
EU Resource Efficiency Scoreboard (RES)	[34]
Recycling Indices (RIs) for the CE	[37]
Resource Productivity (RP)	Wen and Meng (2015)
Reuse Potential Indicator (RPI)	[3]
Recycling Rates (RRs)	[37]
Sustainable Circular Index (SCI)	[15]
Value-based Resource Efficiency (VRE)	[100]
Zero Waste Index (ZWI)	[15]
Whole building circularity indicator (WBCI)	[61]
Product Circularity Index (PCI),	[94]
Element Circularity Index (ECI)	[94]
Critical Success Factors (CSFs)	[76] [62]
Reuse Potential Indicator (RPI)	[10, 78]
Whole-Life Performance Estimator (WLPE)	[6]
Circular Economy Performance Indicator (CPI)	[56]
Global Resource Indicator (GRI)	[2]
Deconstruction, and Resilience (3DR)	[75]
System Circularity Indicator (SCI)	[11]
The Circular Construction Evaluation Framework (CCEF)	[29]
The Disassembly and Deconstruction Analytics System (D-DAS)	[5]

product within the same industry. The MCI is primarily composed of three key product characteristics: the amount (V) of used virgin raw materials, the amount (W) of unrecoverable waste attributed to the product, and the utility factor (X) that accounts for the lifetime of the product. MCI is determined by considering the proportion of material input (virgin or non-virgin), the material output (either energy recovery or landfill disposal), and the technical lifecycle of a product. These factors collectively represent the theoretical circular capacity of each product. To calculate the MCI for each product, a Bill of Materials (BoM) is utilised as input. The MCI represents 50% of the circular potential of products [11]. From this perspective, the MCI is not just a simple indicator but a more complex assessment method for measuring material circularity. In the fourth section, the focus is driven to the specifics of the MCI and its integration with other components to form the Building Circularity Indicator (BCI), providing a complete methodology for circularity assessment.

16.4 Development of Circularity Indices: Aggregation of Indicators

Generally, criteria and indicators are quantitative or qualitative measures created from a collection of observed facts that might reflect relative positions in a certain area [23]. They can show the change in direction across time and between various units when it is reviewed regularly. They can also be useful in establishing policy priorities, benchmarking, and performance monitoring. When separate indicators are combined into a single index (sometimes called ranking, method, or tool) based on an underlying model, the resulting indicator is generally referred to as an "index" or aggregated indicator [86]. Ideally, the index should measure multidimensional aspects such as competitiveness, industrialisation, sustainability, single market integration, and knowledge-based society, which a single indicator cannot adequately represent. Table 16.2 presents a list of pros and cons of indices, which was originally evaluated by the Joint Research Centre-European Commission in 2008.

An index quality and the validity of the information it delivers largely depend on the framework and data used rather than only the methodology employed in its creation [52]. Despite the employment of cutting-edge methodology in its creation, an index built on a weak theoretical foundation or soft data with significant measurement errors may produce policy statements that are open to debate. The experience demonstrates that disagreements regarding the best way to create weights are difficult to settle. Science may considerably contribute to ensuring that the processes of aggregation are as sound and transparent as feasible, although it cannot give an objective approach for creating the only true index to summarise a complex system. Therefore, in this part, a generic index generation framework is given to guide aggregators like a checklist for constructing an index (See Fig. 16.1).

Building an index begins with a strong theoretical framework step. The framework should explicitly identify the phenomenon to be assessed and its constituent parts, choosing distinct indicators and weights (see the previous section) that reflect the

Table 16.2 Pros and Cons of Aggregated Indicators (Indices) (Adapted from [86], OECD 2008)

Pros	Cons
Indices can be used to summarise complicated or multifaceted problems	Indices that are poorly constructed or evaluated may lead to false or incomplete understandings
They can simplify classification based on challenging criteria	The judgement required to form indices can introduce subjectivity
They facilitate the interpretation of trends across a variety of distinct metrics	Indicators necessitate data, which is sometimes unavailable or inaccessible, making its acquisition time-consuming or resulting in inaccurate calculations
They help fit more data into the allotted space or streamline a list of indicators	If the construction process is not transparent, it may obscure serious flaws in some dimensions and make it more difficult to identify appropriate corrective action

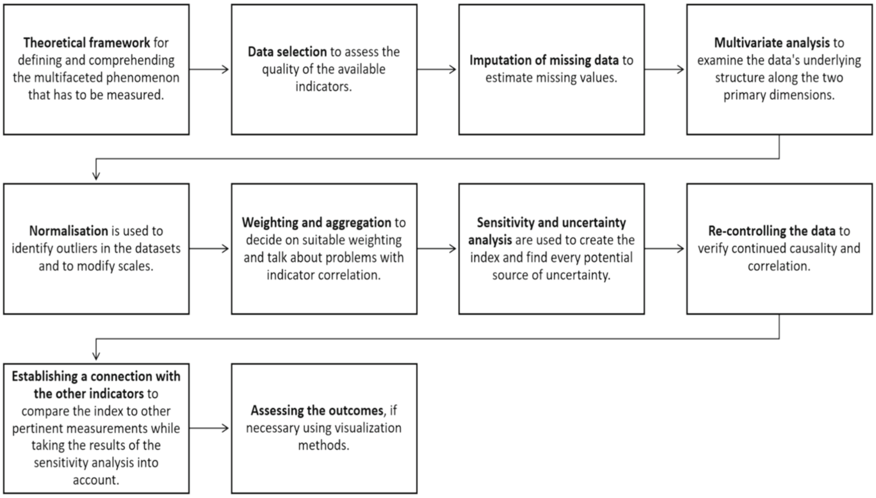

Fig. 16.1 A generic framework for index generation steps (*Source* own elaboration)

relative weights of these components and the dimensions of the final composite. The ideal approach would be to base this procedure on what is desirable to measure rather than on which indicators are readily available.

Within the data selection step, the quality of the underlying variables significantly impacts both the indices' strengths and flaws. Variables should ideally be chosen based on their applicability, analytical quality, timeliness, and accessibility. With advancements in data selection and indicator development, aggregated indicators' quality and accuracy should also advance. Missing data frequently hampers the creation of reliable indices. Both random and non-random data loss is possible. In this situation, a step for imputation of missing data should be managed. Variance estimations should consider the uncertainty in the imputed data. Because of this, the analysis can now account for the impacts of imputation. Single imputation, however, is notorious for underestimating variance because it only fully accounts for imputation uncertainty. The multiple imputation approach, which offers numerous values for each missing value, can better capture the uncertainty brought on by imputed data.

More decision-makers need to create aggregated indicators than ever before. In most cases, the choice of a single indicator is made randomly, with little thought given to how that signal may interact with other indicators. Therefore, the data set's applicability may be evaluated by applying multivariate analysis (MVA), which also helps to understand how the methodological decisions will impact the results. The most common MVA methods are Multiple Linear Regression Analysis, Principal Components and Factor Analysis, Cronbach Coefficient Alpha, and Cluster Analysis, which are briefly explained in Table 16.3.

Table 16.3 Multivariate analysis techniques for aggregating indicators (OECD, 2008)

Analysis Name	Mathematical Formulation	Advantage	Disadvantage
Multiple Linear Regression	$\hat{Y} = a + b_1 X_1 + \cdots + b_n X_n$ where $\hat{Y}$ is the indicator, a is a constant, and b_1 to b_n are the regression coefficients (weights) of the associated sub-indicators $X_1, X_2 \ldots, X_n$	Managing many diverse variables	For other ranges, the output uncertainty might not hold
Principal Components & Factor Analysis	$Z_j = \sum_{i=1}^{p} a_{ij} X_i, j = 1,2, \ldots, p$ takes p variables $X_1, X_2 \ldots, X_p$ and finds linear combinations of these to produce principal components $Z_1, Z_2 \ldots, Z_p$ that are uncorrelated	One important feature in evaluating various statistical aspects of the data is the absence of correlation	Not usually efficient since many original variables are reduced to a small number of modified variables
Cronbach Coefficient Alpha	$\alpha = \frac{p.\bar{r}}{1+(p-1).\bar{r}}$ number p of indicators and the average inter-correlation $\bar{r}$ among the indicators	The strength of correlations between groups of sub-indicators can be evaluated by researchers by using a coefficient of dependability, also known as consistency	Results can be positively or negatively impacted by sample size, and low-reliability scores are usually associated with fewer items
K-means Clustering Analysis	$J = \sum_{j=1}^{K} \sum_{n \in S_j} \left\|x_n - \mu_j\right\|^2$ n examples to one of k clusters, where n is the sample size and k	Presenting an alternate technique for grouping nations and illuminating the composition of the data set	Only descriptive; might not be transparent if methodological choices made during the investigation are not well supported and given adequate context

16.4.1 Common Weighting and Aggregation Methods

The sub-indicators that are measured in various units must be converted to the same unit before an index can be calculated. Choosing the appropriate weights is the more challenging issue [105]. Six possible approaches to calculating an indicator are represented by equations in Table 16.4 [87]. These vary from the most straightforward (Method 1) to the most intricate (Method 6). There are additional ways to calculate a composite indicator. Each method has several variations. Each of the given methods is briefly explained in this part.

Table 16.4 Methods for calculating indices for country c (Adapted from [87])

	Method	Equation
1	Total ranking of countries	$CI_c^t = \sum_{i=1}^{N} Rank_{ic}^t$
2	The sum of the indicators above and below the mean for each indicator	$CI_c^t = \sum_{i=1}^{N} sgn\left[\frac{x_{ic}^t}{x_{EU_i}^t} - (1+p)\right]$
3	Ratio or percentage of variance from the average	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t}{x_{EU_i}^t}$
4	Variation in the annual percentage	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - x_{ic}^{t-1}}{x_{ic}^t}$
5	Standardised values	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - x_{EU_i}^t}{\sigma_{EU_i}^t}$
6	Re-scaled values	$CI_c^t = \frac{\sum_{i=1}^{N} w_i \times y_{ic}^t}{\sum_{i=1}^{N} w_i}$, where $y_{ic}^t = \frac{x_{ic}^t - min(x_i^t)}{range(x_i^t)}$

$^* x_{ic}^t$ is the value of indicator i for country c at time t. $w_i w_i$ is the weight given to indicator i in the composite index. In Method 2, p = an arbitrarily chosen threshold above and below the mean

The first method is the simplest aggregation technique among the methods given in Table 16.4. For each sub-indicator, the variables (e.g., countries) are ranked, and the rankings are then added up. Therefore, ordinal levels are the foundation of this method. Its simplicity and independence from outliers is its merits. Its drawback is that absolute-level information is lost. Method 2 solely uses data at the nominal level for each indicator. It only calculates the difference between the number of indicators above and below a mean-cantered threshold. The simplicity of the procedure and the fact that it is unaffected by outliers are its benefits. This method's drawback is that interval-level information is lost. Method 3 averages the ratios (or percentages) close to each indicator's mean. It has the benefit of allowing for the calculation of changes in the composite indicator over time. However, there is a significant drawback to this approach. In the presence of outliers, it is less resilient. Method 4 substitutes the sub-indicator values for the differences between the current year and the prior year and divides those values by the value from the prior year. Method 5 has been frequently employed in various indexes, such as the environmental sustainability index. The index is calculated using the standardised scores for each indicator, which are calculated as the difference between each indicator's score for each variable and the mean divided by the standard error. Compared to Method 3, this approach is more resilient when handling outliers, but it does not provide a complete solution. This is since each indication will have a different range between the least and maximum observed standardised scores. An indicator in the variables with extreme values is given more weight by the approach. In contrast to Method 5, Method 6 employs rescaled values for the constituent indicators. As a result, the standardised scores for each indicator have the same range. Due to this, this technique is more resilient in the presence of outliers.

Some weighting and aggregation techniques are generated from statistical models like Data Envelopment Analysis (DEA) and Unobserved Components Models

(UCM) or from participatory techniques like Budget Allocation Procedures (BAP), Analytic Hierarchy Processes (AHP), and Conjoint Analysis (CA) [32, 104].

Since the indicators in a data set frequently have distinct measurement units, normalisation is necessary before any data aggregation as part of the one-step-ahead framework technique. The following section presents the normalisation techniques in the context of nine different formulations.

16.4.2 Common Normalisation Methods

Normalisation is necessary before any data aggregation since the indicators in a data set frequently have distinct measurement units [81]. There are numerous normalisation techniques, which are summarised in Table 16.5. However, choosing an appropriate method is not simple and requires specific consideration for potential scale adjustments, transformations, or severely skewed indications. The data qualities and the goals of the composite indicator should both be considered when choosing the normalisation approach. To evaluate their effect on the results, robustness tests may be required [69].

According to WBCSD (2018), a circularity assessment method built on a well-liked current tool is more likely to be adopted than to produce something entirely new. As a result, many indicators are created using already available technologies. However, a small number of authors created their framework by defining a wide variety of circular KPIs and employing varied research approaches, according to [60]. In the highlight of these implications, a circularity index generation methodology for a new building process is presented as a conceptual framework design for circularity assessment mainly due to the indicated steps in this field. The following part provides some selected case studies of the developed tools by focusing on their methodologies.

16.5 Examples of the Circularity Indices for New Building Assessments and Their Methodologies

This section includes MCI and BCI-based tools as well as the Circular Construction Evaluation Framework (CCEF) and Disassembly and Deconstruction Analytics System (D-DAS). The selection of indicators, their derivatives, and specific frameworks was based on their widespread use within the field, considering their value in evaluating the circularity of building materials and construction processes. Each of these chosen metrics or frameworks offers a quantifiable means to assess the efficiency of resource management, reuse, and recycling within the construction industry. The major challenge in CE lies in standardising these indicators, prompting the combination of the most prevalent ones into a cohesive framework. This approach

Table 16.5 Generic normalisation methods analysing country c (Adapted from [87])

	Method	Equation
1	Ranking	$I_{qc}^{t}=Rankx_{qc}^{t}$
2	Standardisation (or z-score)	$I_{qc}^{t}=\frac{x_{qc}^{t}-x_{qc-\tau}^{t}}{\sigma_{qc-\tau}^{t}}$
3	Min–Max	$I_{qc}^{t}=\frac{x_{qc}^{t}-min_{c}(x_{q}^{t0})}{max_{c}(x_{q}^{t0})-min_{c}(x_{q}^{t0})}$
4	Distance to a reference country	$I_{qc}^{t}=\frac{x_{qc}^{t}}{x_{qc-\tau}^{t0}}$ or $I_{qc}^{t}=\frac{x_{qc}^{t}-x_{qc-\tau}^{t0}}{x_{qc-\tau}^{t0}}$
5	Categorical scales	e.g. $I_{qc}^{t}=$ $\{0ifx_{qc}^{t}<p^{15}20ifp^{15}\le x_{qc}^{t}<p^{25}40ifp^{25}<x_{qc}^{t}<p^{95}100ifp^{95}\le x_{qc}^{t}$
6	Indicators above or below the mean	$I_{qc}^{t}=\{1ifw>(1+p)0if(1-p)\le w\le(1+p)-1ifw$, where $w=\frac{x_{qc}^{t}}{x_{qc-\tau}^{t0}}$
7	Cyclical indicator (OECD)	$I_{qc}^{t}=\frac{x_{qc}^{t}-E_{t}(x_{qc}^{t})}{E_{t}(\left\|x_{qc}^{t}-E_{t}\left(x_{qc}^{t}\right)\right\|)}$
8	Balance of opinions (EC)	$I_{qc}^{t}=\frac{100}{N_e}\sum_{e}^{N_e}sgn_{e}(x_{qc}^{t}-x_{qc}^{t-1})$
9	Percentage of annual differences over consecutive years	$I_{qc}^{t}=\frac{x_{qc}^{t}-x_{qc}^{t-1}}{x_{qc}^{t}}$

*x_{qc}^{t} is the value of indicator q for country c at time t. $\underline{C}$ is the reference country. The operator sgn gives the *sgn* of the argument (i.e. + 1 if the argument is positive and -1 if the argument is negative). N_e is the total number of experts surveyed. p^{i} is the i-th percentile of the distribution of the indicator x_{qc}^{t} and an arbitrary threshold around the mean

provides a unified means of evaluating circularity in the context of construction practices.

16.5.1 Material Circularity Indicator (MCI)

The first example is the indexing method details of the MCI, which is already discussed in the previous parts for indicator selections and developments. The MCI value ranges from 0 to 1, with a higher number indicating a higher level of circularity. The MCI is a multidimensional assessment that considers several factors. Firstly, the MCI primary input is the comprehensive analysis of the proportion of resources derived from both virgin and recycled materials, as well as components that have been repurposed from previous usage.

Secondly, the MCI also considers utility derived during the product's usage phase. This evaluation involves a comparative assessment of the duration and intensity of product use in relation to industry norms for similar product types. Along with the product durability assessment, the analysis extends to account for scenarios involving repair, maintenance, and shared consumption business models. Thus, the MCI can assess if the product has the potential to exceed its planned durability, prolonging its use in the industry.

The subsequent focus of the MCI is the post-usage phase, with a critical examination of the material destination after being used. This involves quantifying materials designated for landfill disposal or energy recovery and those designated for recycling. Moreover, the MCI identifies components with the potential to reuse, reducing waste generation and optimising resource use. Moreover, the MCI also evaluates the efficacy of recycling processes. This assessment considers the efficiency of recycling protocols in generating and recycling input materials at the product's end-of-life stage, profoundly influencing product circularity and minimising resource consumption and environmental impact. Finally, the detailed bill of materials is essential for the MCI itemising and quantifying data for all components and materials. Additionally, the MCI can incorporate optional risk and impact indicators for products (e.g., material price variation, material supply chain risk, material scarcity and toxicity, energy usage, and CO_2 emissions) to provide further insights related to the business concerning the product [37].

Mathematically, the MCI for a product can be defined through the Linear Flow Index (LFI) of the product, along with the factor F(X), which is constructed as a function F of the utility X. This utility factor determines the impact of the product's utility on its MCI [37]. There are multiple case studies that utilised the MCI for the circulatory assessment [60, 82]. However, MCI has a few limitations. Firstly, it focuses solely on the materials that ultimately become finished products, neglecting any losses that may occur during extraction, transportation, and manufacturing processes. Secondly, the MCI tends to overestimate the quality of recovered products, assuming they are equivalent to newly produced ones. Thirdly, it fails to consider the significance of biological materials in the transition from a linear to a circular economy [60].

Moreover, Jiang (2022) argues that the MCI excessively relies on the mass of the product, which may not accurately reflect the value of a specific material. This has raised a debate about the practice of simply summing up the MCIs of individual materials to calculate the MCI of a product, as it may overestimate its circular value due to challenges in separating materials for recovery at the end of life in many instances. [57] modified the MCI to overcome these limitations by employing economic value (E) as the unit of measurement and introducing a new indicator known as residual value (R).

16.5.2 Building Circularity Indicator (BCI)-Based Tools

The first version of the Building Circularity Indicator (BCI) model was introduced by [98] to measure the extent to which the linear flows have been minimised and restorative flows maximised for four levels of detail in a building: Material, Product, System, and Building. The model implies a bottom-up approach to calculate the indicators at the four levels, scaling up from the Material Circularity Indicator (MCI), which was first introduced by the Ellen McArthur Foundation (2015), consecutively to the Product Circularity Indicator (PCI), then the System Circularity Indicator (SCI) up to the overall Building Circularity Indicator (BCI). The general idea behind the BCI is to look at the input, usage, and output. This model should also be used to communicate between chain partners in the construction process.

The research methodology followed in this model is built upon an extensive list of KPIs obtained from expert semi-structured interviews, then a subjective prioritisation by the author to shorten the list, providing a set of the most important circularity indicators that later is validated by an expert panel. The previous process resulted in a conceptual framework that was translated into an assessment methodology and eventually tested and validated on a case study using Excel functionality.

The final set of KPIs is categorised into three groups of indicators:

1. Technical requirements: these consider the type of input and output, the technical lifetime, and the disassembly factors for only technical cycles
2. Preconditions: these involve aspects of material health, GHG emissions, renewable energy use, and environmental impact.
3. Drivers: these encompass material scarcity, potential financial value, and future reuse possibilities

The circularity indicators only include the technical requirement of materials that should be considered. The preconditions and drivers are designed to give principals (organisations) the possibility to incorporate their interests even better. The preconditions may provide additional information to evaluate if the changing level of material circularity affects other impacts or interests of principals and their stakeholders (e.g., energy and water). Drivers could not be seen as real indicators but more as a value proposition.

The distinction between the indicators at different hierarchical building compositions of material, component, system, and full building scales of assessment allows us to identify the relevant criteria and indicators to the materials and products separately, but also the interconnections and physical interfaces at the assembly in a building. At a material level (MCI), the material input and output and the utility of a product, depending on its technical lifetime, are evaluated. At the product level (PCI), the interfaces and connections between products and materials are considered based on the Design for Disassembly (DfD) principles and possibilities, including aspects of functional, technical, and physical deconstruction. At the system level, the SCI assesses the circularity of products in a system together based on their weight of sales revenues and makes the separation of a system based on the shearing layers to compare systems with each other and the different lifetimes of each system. Finally, at a building level, the BCI assesses the separate systems as a whole with a factor for the level of importance of each system.

The overall aspects considered in the circularity calculation methodology, technically, only consist of two components: (1) the material specifications and (2) the design for disassembly (functional, technical, and physical). The BCI by Verberne formed the first circularity assessment tool for a whole building level and introduced an important base for later building circularity models, which built upon it and addressed some of its limitations. For example, [96] refined the BCI by addressing certain limitations related to design for disassembly (DfD) and the weighting of factors. [95] expanded the BCI by introducing circularity criteria for foundations. [103] proposed an automated framework using BIM that further developed Verberne's original BCI. [61] enhanced the model by incorporating adaptability factors.

Cradle to Cradle Certified is among the prevalent models for assessing circularity in building projects, evaluating products based on criteria such as material health, reutilisation, renewable energy, water stewardship, and social equity [28]. BREEAM, primarily focused on environmental assessment, incorporates principles of the circular economy related to materials use and life cycle impacts (Building Research Establishment (BRE), n.d.). LEED, developed by the U.S. Green Building Council, promotes sustainable practices in design, construction, and operation, emphasising materials and resources aligned with circular economy principles [91]. The Ellen MacArthur Foundation's Circulytics measures circular economy performance across business dimensions [39]. Malaysia's Green Building Index (GBI) rates buildings based on sustainable material use and life cycle impacts, aligning with circular economy principles (Green Building Index Malaysia, n.d.).

Despite their importance in advancing sustainability in construction, these models face significant challenges. They often require substantial resources for data collection, analysis, and verification, which can be daunting for smaller organisations or projects with limited capabilities. Moreover, their focus tends to be on inputs like material selection and energy efficiency, rather than on assessing outputs such as actual circularity achieved or the effectiveness of recycling and reuse processes [71]. This gap between input-focused assessments and real-world circular outcomes can hinder their ability to comprehensively achieve sustainability goals. Furthermore, while these models address lifecycle impacts to some extent, they may not fully encompass critical stages such as end-of-life scenarios or the management of materials post-demolition or renovation [14]. Certification costs also pose barriers, as the expenses associated with assessments and audits can be prohibitive, especially for projects in developing regions [101]. Additionally, the adaptability of these models to diverse regional contexts and regulatory frameworks varies, potentially limiting their global applicability. Balancing complexity with practical application remains an ongoing challenge, requiring continuous refinement to ensure these models effectively support sustainable and circular practices across different scales and contexts within the building sector.

In contrast, modern BCI-based tools offer robust features that distinguish them from traditional building circularity models. These tools integrate comprehensive circular economy principles throughout the building lifecycle, encompassing not only material health and energy efficiency but also critical aspects like end-of-life recycling and reuse. They adopt a holistic assessment approach that balances inputs such as material selection with outputs like actual circularity achieved and the recyclability of materials post-use, providing a more accurate measure of sustainable practices [88]. Utilising advanced data analytics and digital technologies, these tools streamline data collection, analysis, and reporting, making sustainability assessments more efficient and accessible across diverse projects. Customisable criteria tailored to regional contexts enhance their global relevance and applicability, fostering transparency and stakeholder engagement. Furthermore, modern tools emphasise performance-based metrics, enabling continuous improvement and benchmarking against sustainability goals. Innovations such as digital twin simulations optimise building performance and resource efficiency. These advancements collectively enhance the capacity of modern building circularity indicator-based tools to drive sustainable and resilient building practices in today's dynamic environment.

16.5.3 HOUSEFUL's Building Circularity Methodology (BCM)

The Horizon 2020 HOUSEFUL project on "Innovative circular solutions and services for new business opportunities in the EU housing sector" (2018–2022) recently reported a methodology to evaluate circularity degree in the sector of housing to be implemented at the earlier stages (new and retrofitted) of building design, as an originally circularity measure via a global circularity indicator, the BCS, Building Circularity Score [49]. The HOUSEFUL approach, using a composed circularity indicator, is fundamental on the degree of circularity based on six pillars—.e., energy, water, and material balances,social and environmental impacts; and life cycle cost reduction. Being the proposed indicator under a life-cycle-based methodological approach, it is aligned with common and existing methods of building sustainability, such as the CEN Technical Committee 350 (CEN TC 350) and the European Union (EU) LEVEL(s); including potential for improvements regarding water and energy circularity per life cycle stage. The six pillars encompass a set of meaningful Key Performance Indicators (KPIs) and weighting factors (energy and water consumption, materials usage, social added value, and life cycle economic value), which are extensively implemented in the sustainable construction sector to result in a single circularity KPI, the so-called BCS [49]. The methodology was applied in the HOUSEFUL demo buildings and related projects, being tested and validated in practice with real data and in different scenarios by comparing different buildings—i.e., location, use, measures, etc. (González et al., n.d.).

The Building Circularity Methodology (BCM) was proposed as a multidimensional model to assess and evaluate the circularity degree in residential and/or tertiary buildings (housing sector), highlighting its implementation in the EU countries under a Circular Economy (CE) perspective. This methodology and the BSC constitute a consistent and reliable output aimed at applying market-usable and innovative solutions accessible to data on current circularity degrees. Thus, it would be useful to inform existing policies and strategies on circularity in the urban built environment and to provide recommendations to the construction sector stakeholders—e.g., designers, manufacturers, promoters, decision-policy, lawmakers, and end-users. Moreover, the HOUSEFUL approach and indicator, which is based on easy and objective metrics, would bring green funding opportunities under the umbrella of administrations and other public bodies and tenders and novel project calls towards the implementation, achievement and promotion of CE principles in the urban built environment. The BSC would be automatically calculated by providing input data on the HOUSEFUL web-based Circularity Tool (CT), as a Software-as-a-Service (SaaS) tool facilitating decision-making and future planning and the design at the construction phase [49].

As highlighted above, the HOUSEFUL's Building Circularity methodology was developed by considering the CE principles of recyclability, reusability and waste management related to materials and buildings on energy and water life cycles, and economic and social performance, as well as circular solutions feasibility. Moreover, new and existing methodologies on CE pillars were considered—e.g., Life Cycle Assessment (LCA), Life Cycle Cost (LCC), and Social Life Cycle Assessment (S-LCA). Additionally, the HOUSEFUL approach is also well-matched with sustainable building certifications—e.g., LEED, BREAM, WELL [49]. The comprehensive circularity calculation, at building level characterisation and its indicators, complements the BCS by the above-mentioned six-pillar consideration. Thus, circularity degree valuation at the lifecycle stage level would provide and identify solid knowledge on improvements and solutions among different CE aspects (pillars), thus improving and unifying building circularity [47].

16.5.4 Circular Construction Evaluation Framework (CCEF)

The Circular Construction Evaluation Framework (CCEF), proposed relatively recently by [29], aims at evaluating the degree of a project's circularity. It addresses both existing and new (proposed) design and construction projects and can be used by a variety of contributors and participants in a project's development (e.g., clients and other professionals in the sector). Its methodological approach consists of the quantification of the level of the examined project's circularity with regard to several relevant criteria.

The assessment takes place on a whole-building basis and at the level of building elements. The circularity credentials for each one of these levels are quantified by different criteria organised in broader groups. Specifically, when the whole building is considered, 14 criteria are employed, classified under four groups [29]:

- Recorded information design, data, and materials: 1. Disassembly plan included in design drawings and specifications, 2. Disassembly sequencing information, 3. Clarity and transferability of plans and specifications,
- Adaptability in design: 4. Versatility (in regular use, cosmetic change), 5. Convertibility (partition/space changes), 6. Expandability (vertical, without major foundation modification), 7. Expandability (horizontal, compatible foundations)
- Simplicity in design: 8. Parts per element, 9. Standardisation and modularity of elements (dimensions), 10. Standardisation and modularity of elements (component variation), 11. Standardisation and modularity of elements (connections), 12. Degree of element independence and classification of construction
- Health and safety: 13. Toxicity/synthetic chemicals, 14. Ease of access, construction, and disassembly

The respective structure at the assessment level of elements comprises 11 criteria that are classified into three groups and three criteria not belonging to a larger thematic area [29]:

- Durability: 1. Number of previous design lives/uses, 2. Length of previous design lives, 3. Predicted length of current design life
- Material inventory: 4. Suppliers and production, 5. Warranties, 6. Donor building(s), 7. Reclaimed and/or recycled content, 8. Involvement of reuse in cleaning or restoration work, 9. Life Cycle Analysis with end-of-life Scenario and Environmental Product Declaration
- Finishes/Treatment: 10. Synthetic/chemical/wet resins/adhesives? (yes/no response) 11. Chemical coatings, 12. Reversibility of connections, 13. Reusable (without restoration or modification), 14. Recyclable (no downgrading)

The rating in the context of each criterion ranges from 0 to 5, with higher scores indicating a higher degree of circularity. This scoring scale is also used for criteria of a qualitative nature (e.g., yes/no reply), so that quantitative final results are achieved. The evaluations at the element- and at the whole building level take place separately and result in two separate scores. Regarding the objectivity of the results, the authors formulating the framework point out the possibility of "an element of bias" [29], p. 6). The structure of the framework's computational implementation provides the possibility for weightings' determination and introduction (however, such development is unavoidably accompanied by a subjectivity factor).

As indicated by the aforementioned criteria, circularity aspects heavily considered within this framework are, among others, design for adaptability and disassembly, as well as materials' reuse. LCA/EPDs related issues, durability and reusability, toxic or synthetic substances creating health risks or preventing direct reuse of components, and several other parameters (simplicity, methods of construction), all seen under the light of a lifecycle approach also considering past and future design lives and uses, are also included in the performed assessments.

16.5.5 Disassembly and Deconstruction Analytics System (D-DAS)

The disassembly and deconstruction analytics system (D-DAS) is a framework enabling the integration of end-of-life performance evaluation/consideration into the buildings' design stage and process [5]. The system's main target evolves around the selection of materials, already in the building's design stage, that will contribute not only to efficient materials' use but also to the reduction of waste at the end-of-life with regard to the built environment. D-DAS uses and builds upon the capabilities of building information modelling (BIM). Allowing the consideration of various alternative solutions for the building design at various levels (materials selection, etc.) and providing the possibility for access to extensive information on the building as well as for complex computational processes, visualisation, and simulation, this system can serve as a decision support tool.

Four layers of D-DAS architecture work together as a single system. The data, based on which the calculations are made, are related to building design (parametric building models, materials, etc.), to the building materials' specification (materials' properties and status), as well as to deconstruction and demolition information (historical data). The system comprises five functional models and analytics: (i) Building Whole Life Performance Analytics, related to the calculation/estimation of the building's performance over time; (ii) Building Element Deconstruction Analytics, resulting in an evaluation of the building design with regard to whether and to which degree design for deconstruction is supported (the applied model is based on Deconstructibility Assessment Score [7], (iii) Deconstruction Arising Analytics, forming the basis for the Pre-Deconstruction Audit generation (iv) Design for Deconstruction Advisor, which identifies possible optimisation points in the design (building components- and materials wise) regarding the materials reuse and the reduction of waste, and provides alternative solutions; (v) Deconstruction Visualisation, providing the plan of the deconstruction process, as well as its visualisation (along with the disassembly process). Each one of these entities supports a different functionality. According to [5], D-DAS can be implemented either as a plug-in for an existing BIM or as a standalone application (visualisation and simulation tools-based).

The implementation of D-DAS presented by [5] is a plug-in to Autodesk Revit, including the functional modules (i), (ii), and (iii). It was validated through the examination of three alternative scenarios for a building. However, important assumptions and simplifications were adopted in this process [13], creating the need for further testing and validation of the system.

16.6 Insights for Future Work and Further Improvements

This section offers valuable insights into the challenges faced by the construction industry in developing circularity assessment tools. To promote more sustainable construction practices and advance the field of circularity assessment, we need to identify several areas for future improvements.

- **Standardisation of Circularity Assessment**: The critical review in this section highlights that one of the main challenges is the lack of a standardised approach to circularity assessment. Therefore, future research should focus on developing sector-wide standards and guidelines for assessing circularity in construction projects. This would streamline the evaluation process and make it easier to compare different projects.
- **Development of Automated Tools**: As mentioned, there is a need for more automated circularity assessment tools, especially in the early design phase. Researchers and software developers should work together to create user-friendly software that integrates circularity assessment seamlessly into Building Information Modelling (BIM) workflows. This will help architects and designers make informed decisions from the outset, reducing the risk of rework in later project phases.
- **Enhanced Data Availability**: The circular economy addresses the importance of data sharing and availability within the current design workflow, where uncertainty and incompleteness prevail, and is addressed in this review as a significant challenge. Future research should explore ways to improve data collection and sharing, possibly through collaborative platforms and databases specifically tailored for circularity assessment in construction.
- **Policy Support**: The section also mentions a perceived lack of supportive policies to improve reuse and recycling in the construction industry. Advocacy for and development of policies that incentivise circular construction practices, such as tax incentives or procurement regulations, can significantly accelerate the adoption of circularity principles.
- **Circularity Indicator Classification and Standardisation**: There is a confusion arising from the interchangeable use of circular terminology. Future work should focus on classifying and standardising circularity indicators, indices, and frameworks to provide a clear and consistent language for circularity assessment in the construction sector.
- **Innovative Circularity Indicators**: Researchers should explore and develop new circularity indicators tailored to the construction industry's unique attributes. These indicators should consider factors such as building service life, diverse materials, stakeholder involvement, and customisation.
- **Interdisciplinary Collaboration**: Circular construction is a complex field that requires expertise in materials science, architecture, engineering, policy, and economics. Encouraging interdisciplinary collaboration among these experts can help foster a holistic approach towards assessing circularity and promoting innovation.

- **Qualitative and Semi-Qualitative Approaches**: While quantitative indicators are essential, it is equally crucial to explore qualitative and semi-qualitative approaches for circularity assessment. These approaches may offer a better understanding of the social and environmental dimensions of circular construction.
- **Education and Training**: To promote the adoption of circularity in the construction industry, it is vital to develop training programmes and educational resources for professionals and stakeholders. Building a skilled workforce that understands the principles and benefits of circularity is essential.
- **Longitudinal Studies**: Longitudinal studies that track the impact of circular construction practices over time can provide valuable insights into their effectiveness. Monitoring the performance and environmental impact of circular buildings throughout their lifecycle and integrating them into existing assessment tools can be a useful strategy.

In conclusion, the construction industry is undergoing a transformation towards circular economy principles. However, to further advance this shift, it is essential to address challenges like standardisation, data availability, policy support, and the development of innovative tools and indicators. With these improvements, the construction industry can become a more sustainable and circular sector, contributing to a greener future.

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