Author/s:
Muñoz, S;Hosseini, MR;Crawford, RH

Title:
Towards a holistic assessment of circular economy strategies: The 9R circularity index

Date:
2024-06

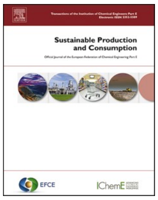
Citation:
Muñoz, S., Hosseini, M. R. & Crawford, R. H. (2024). Towards a holistic assessment of circular economy strategies: The 9R circularity index. Sustainable Production and Consumption, 47, pp.400-412. https://doi.org/10.1016/j.spc.2024.04.015.

Sustainable Production and Consumption 47 (2024) 400–412

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



Towards a holistic assessment of circular economy strategies: The 9R circularity index

Santiago Muñoz[a,*], M. Reza Hosseini[b], Robert H. Crawford[b]

[a] Faculty of Science, Engineering and Built Environment, Deakin University, 1 Gheringhap St, VIC 3220, Geelong, Australia
[b] Melbourne School of Design, The University of Melbourne, Victoria 3010, Parkville, Australia

ARTICLE INFO

Editor: Prof. Raymond Tan

Keywords:
Materials flow analysis
Life cycle assessment
KPIs
10R framework
Environmental assessment

ABSTRACT

Our planet faces mounting environmental burdens due to linear production and consumption. Circular economy strategies offer a promising alternative, but evaluating their effectiveness requires robust measurement tools. Existing approaches lack a comprehensive framework incorporating the hierarchical strategies proposed by the 9R framework and the butterfly diagram. Based on the current circular economy indicators, this study gathers a set of indicators designed to assess the efficacy of circular economy strategies, considering the hierarchical levels outlined in the 9R framework. Moreover, it leverages the Analytic Hierarchy Process (AHP) fundamental scale as an integration tool to consolidate the suggested indicators into a unified metric termed the “9R circularity index”. This approach relies on a bottom-up approach to measure circular economy at various levels. The “9R circularity index” enhances the ability to compare results from a material flow analysis perspective. In addition, this paper presents a step-by-step approach and a supporting software tool that aims to facilitate the measurement, selection and comparison between circular and linear models. Ultimately, this proposed approach offers a workable, data-driven tool to support the transition towards a circular economy.

1. Introduction

In the contemporary global economy, there exists a notable phenomenon characterised by the accelerated degradation of the environment due to overconsumption and overproduction (Taghikhah et al., 2019). There has been an exponential increase in material consumption and waste generation in the last decades (Reike et al., 2022; UNEP, 2016). Currently, over 100 billion tonnes of raw materials are extracted annually, with material waste estimated to be even beyond that value (Circle Economy Foundation, 2023; UNEP, 2022). These material use and waste statistics are expected to increase in the coming years, as the global population and human demands on the planet's resources are on the rise (Ghafoor et al., 2023). To address this issue, a transition from the current linear economic model (based on a “take-use-dispose” approach) to a more circular economy (CE) model is needed (Circle Economy Foundation, 2023; De Pascale et al., 2021; UNEP, 2022).

Regardless of the expanding body of literature on various dimensions of a CE (Elia et al., 2017; Kirchherr et al., 2023), a persistent gap remains evident; that is, there is no consensus on the way to measure a CE (Calzolari et al., 2022; Reich et al., 2023). The identified gap in the research landscape pertains to the deficiency of a comprehensive framework and the absence of a consensus on the selection of indicators and indexes that can effectively function as robust metrics for evaluating and quantifying CE practices (ACE Hub, 2022; Butković et al., 2021; Shooshtarian et al., 2023). This critical deficiency underscores the need for further scholarly inquiry and deliberation in order to develop a more unified and well-defined methodology for assessing CE initiatives (Harris et al., 2021; Reich et al., 2023).

This area of research has received interest in the last decade (Cagno et al., 2023). Indeed, several practitioners and academics have focussed on defining a framework to measure a CE and indicators to be used as metrics (Calzolari et al., 2022; De Pascale et al., 2021). For instance, over 249 quantitative indicators are currently used as environmental assessment metrics for CE (Muñoz et al., 2023b). This confirms the great variety of approaches currently used by both academics and practitioners (Cagno et al., 2023; Vegter et al., 2023). Within the current scholarly discourse, the practicality of implementing these metrics and their suitability for any specific context under consideration remain subjects of continuous and active research (Reich et al., 2023). As argued by Matos et al. (2023) the existing proposed methodologies and indicators lack standardization, exhibit significant variations in complexity, and in certain instances, display an overly narrow scope of focus. These discrepancies collectively impede their practical adoption.

---

* Corresponding author.
E-mail addresses: smunozvela@deakin.edu.au (S. Muñoz), mreza.hosseini@unimelb.edu.au (M.R. Hosseini), rhcr@unimelb.edu.au (R.H. Crawford).

https://doi.org/10.1016/j.spc.2024.04.015
Received 18 January 2024; Received in revised form 5 April 2024; Accepted 9 April 2024

Abbreviations

CE	circular economy
BSI	British Standards Institution
ISO	International Organization for Standardization
MFA	material flow analysis

Furthermore, upon conducting a comprehensive review of the current approaches and indexes, it becomes evident that none of the identified indexes successfully incorporates the hierarchy within the 10R strategies, including material utilisation and waste generation considerations. This deficiency represents a significant gap in the evaluation framework, given that the 10R strategies serve as the cornerstone and fundamental pillars of the CE concept (Kirchherr et al., 2023; Reike et al., 2022).

This paper aims to address this gap, by introducing a comprehensive set of indicators and indices. The proposed metrics are designed to effectively encompass and evaluate the multifaceted impacts of CE strategies, utilising a material mass perspective and adhering to the hierarchical structure outlined in the 10R framework. The novelty of the approach presented here relies on an integration approach that defines a criteria weighting system that is not biased by expert judgements or context-specific. It merely translates the 10R hierarchical proposition, often referenced in CE definitions, to a quantitative scoring system. Moreover, the bottom-up approach presented here can be used at any CE level (Fig. 5).

2. Literature review

2.1. Indicators and indexes

The indicators and indexes play a vital role in the development of this paper. Indicators are defined as '*simple measures, most often quantitative, that represent a state of economical, social and/or environmental development in a defined region*' (Ness et al., 2007). Indicators provide insights regarding specific phenomena of interest. Moreover, with the aggregation of several indicators or variables, indexes are formed.

Two types of indicators and indexes are relevant to this study. The actual indicators or indexes refer to the current scenarios, while the potential indicators refer to the ideal scenario that can be achieved based on current knowledge and practices. For instance, an actual indicator may measure how much materials are recirculated into creating a specific material or product (e.g., current steel recycled rate and current steel from virgin resources in a cooking utensil). A potential indicator would instead measure the possible end-of-life scenarios that the material can have. For instance, steel is well known for its recyclability potential. Moreover, if the material is used with mechanical joints (e.g. bolts), it may be feasible to disassemble and be reused, while if there are fixed joints (e.g., weld or glued), the potential may be reduced to a lower hierarchy 10R strategy, such as recycle.

One of the most comprehensive definitions for a CE is the one proposed by Zhai (2020), defining a CE as an intentional and purposeful industrial system that emphasises restoration and regeneration over traditional end-of-life concepts. It promotes the use of renewable energy, eliminates toxic chemicals that hinder reuse, reduces waste through improved material design, and operates at various levels, from micro-level (products, companies, consumers) to macro-level (city, region, nation) (Wijewickrama et al., 2021). The goal of a CE is to achieve sustainable development, benefiting the environment, economy, and social equity for both current and future generations (Suárez-Eiroa et al., 2019). Indeed, CE aims to replace the end-of-life concept by proposing a great variety of strategies. Moreover, two cycles are commonly related to the CE definition: the biological cycle (related to organic materials), and the technical cycle (oriented to manufactured materials) (Wouterszoon Jansen et al., 2022). Within the technical cycle, among the most commonly referenced strategies are the ones proposed by the 10R framework (Kirchherr et al., 2023). The 10R framework defines ten hierarchical strategies that aim to reduce material use and waste generation (Fig. 1). From most effective to least effective, the 10R framework strategies are: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover (Kirchherr et al., 2017; Potting et al., 2017). Moreover, the transition from fossil fuel consumption to renewable energy use, and the elimination of toxic materials are also commonly related to the CE definition (Adabre et al., 2023).

2.2. Circular economy assessment/measurement

The imperative of transitioning towards a CE is underscored by the need to address resource depletion and environmental degradation (Kirchherr et al., 2023). This transition hinges on the effective measurement of CE practices through indexes and frameworks, which are not just facilitators but are integral to the realisation and optimisation of a CE (Martinho, 2021; Saidani et al., 2019). Quantitative and qualitative measures, indexes, and frameworks offer a structured approach to gauging the progress and efficacy of CE practices (De Pascale et al., 2021; Martinho, 2021). These tools facilitate a shared understanding and a common language among stakeholders, which is essential for advancing the discussion and implementation of CE (Parchomenko et al., 2019). Moreover, the use of indicators and frameworks in CE is vital for setting and achieving specific, quantifiable targets. By providing a means to evaluate the effectiveness of these strategies, they assist in forging a path towards a more sustainable future (Martinho, 2021) and provide a means to track progress and effectiveness, help in setting tangible goals, and foster a deeper understanding (Parchomenko et al., 2019; Saidani et al., 2019). In essence, their role is central to the successful integration and advancement of CE concepts in both theory and practice (Blomsma and Brennan, 2017; Bocken et al., 2017).

Muñoz et al. (2023b) identified 12 key concepts that inform current CE environmental assessment indicators, and ranked them by the order of their frequency, as stated in Table 1. Furthermore, the authors argued that most of the current quantitative indicators are based on two overarching methodologies: Life Cycle Assessment (LCA), and Material Flow Analysis (MFA), as discussed next.

2.3. Circular economy assessment based on life cycle assessment

LCA is regulated by the International Organisation for Standardization (ISO) 14040 and ISO 14044 standards, which specify an iterative approach based on four phases: 1) goal and scope definition, 2) inventory analysis, 3) life cycle impact assessment, and 4) life cycle interpretation. Following these standards, LCA can be used to measure a great variety of environmental impacts, including greenhouse gas emissions (GHGe), energy consumption, water consumption, and acidification of soil and water, among others.

A great variety of indicators have been currently used and proposed to assess the environmental performance of CE through LCA. Indicators measuring impacts on water and water use (Rönnlund et al., 2016; WBCSD et al., n.d.), global warming potential (GWP) (Ansanelli et al., 2021; Backes et al., 2022; Cradle to Cradle Products Innovation Institute, 2021), chemical use (Cradle to Cradle Products Innovation Institute, 2021; Rönnlund et al., 2016), hazardous materials (ISO, 2017; Lachat et al., 2021; Peceño et al., 2021), ecotoxicity (Bonoli et al., 2020; Fořt and Černý, 2020), energy performance (Colangelo et al., 2020; Lachat et al., 2021; Schützenhofer et al., 2022), renewable energy usage (Lachat et al., 2021; Medina and Fu, 2021; Rönnlund et al., 2016), land use (Colangelo et al., 2020; Peceño et al., 2021; Vitale et al., 2021), land use intensity (Rönnlund et al., 2016), natural land transformation (Niu et al., 2021), mineral substitutability (Ansanelli et al., 2021; Peceño

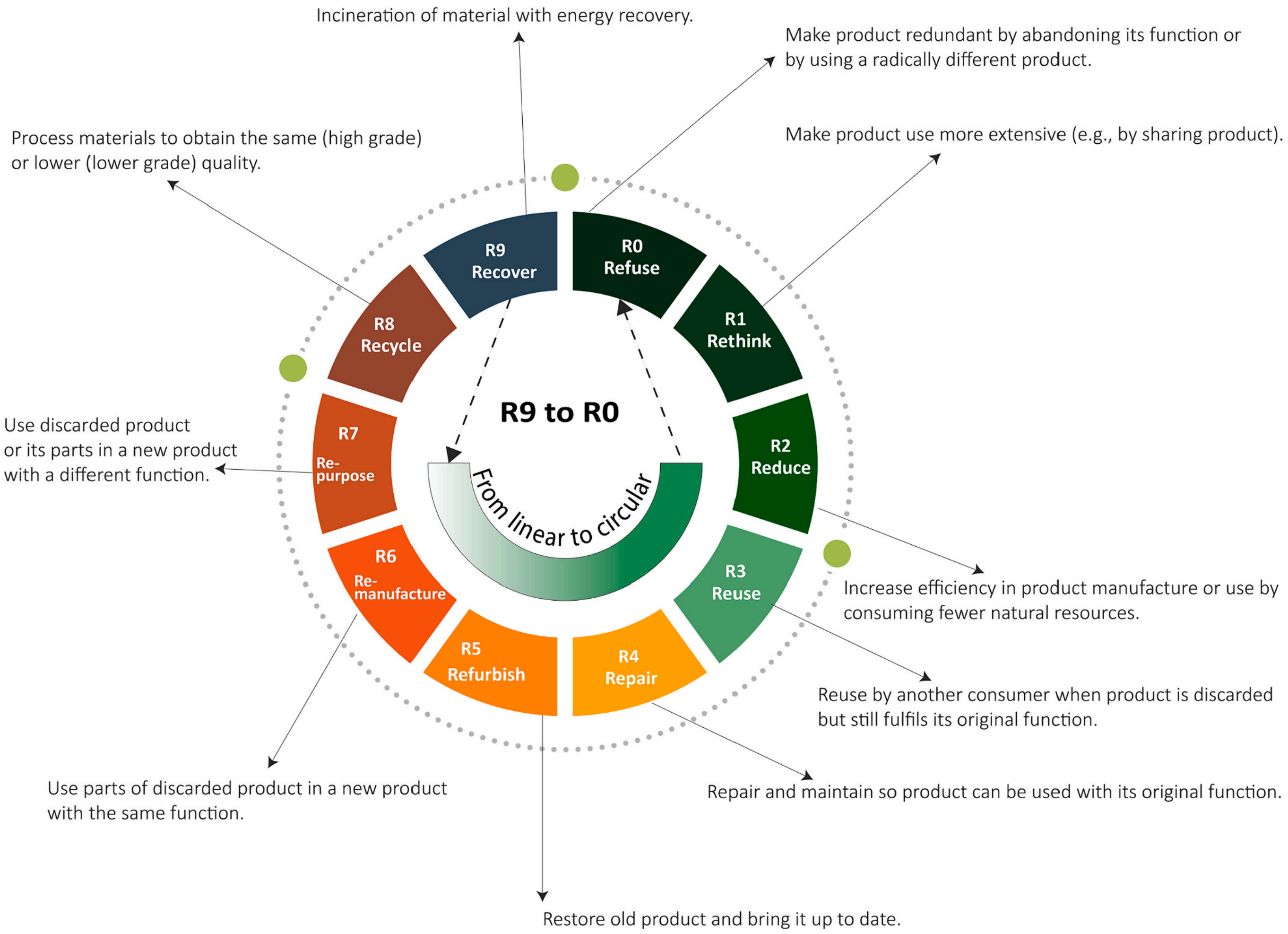


Fig. 1. The 10R framework (adapted from Kirchherr et al. (2017)).

Table 1
Key topics found in current indicators (adapted from (Muñoz et al., 2023b)).

Concept	% indicators covered	Rank	Based on
10R framework	22.37 %	1	MFA
Water	12.94 %	2	LCA
GWP	12.07 %	3	LCA
Material use	10.45 %	4	MFA
Chemical use/ toxicity	8.04 %	5	LCA
Energy	7.83 %	6	LCA
Waste	7.80 %	7	MFA
Connections/ disassembly	3.31 %	8	MFA
Ozone layer	2.68 %	9	LCA
Land use	2.47 %	10	LCA
Lifetime	2.40 %	11	MFA
Acidification	2.27 %	12	LCA
Total	94.64 %		

Note: The missing percentage (5.36 %) relates to indicators that reported other topics.

et al., 2021; Rönnlund et al., 2016), and acidification of both soil (Colangelo et al., 2020; Niu et al., 2021) and water (Lachat et al., 2021; Schützenhofer et al., 2022; Zanni et al., 2018). These are just some examples of indicators for CE assessment based on LCA. Indeed, a great variety of topics are used based on LCA methodology.

2.4. *Circular economy assessment based on material flow analysis*

Similarly, several indicators are currently used and proposed to assess the environmental performance of CE through a material flow perspective. MFA is defined as '*a systematic assessment of flows and stocks of materials within a system defined in space and time*' (Brunner and Rechberger, 2016). MFA is based on the law of conservation matter, stating a mass balance between all inputs, stocks, and outputs of a process. When conducting an MFA, a delimitation of a system boundary is produced, where the assessment of inputs, outputs and material flows are generated to identify how the system behaves from a mass balance point of view. Thanks to this perspective, this methodology is a very attractive approach to be used for resource and waste management. This perspective also makes it very suitable to understand the change in material flows that CE strategies generate.

Currently used indicators based on MFA include indicators such as % materials landfilled (Jiménez-Rivero and García-Navarro, 2016; Tazi et al., 2021), % materials incinerated with energy recovery (ISO, 2017; Medina and Fu, 2021; Tazi et al., 2021), % materials recycled (Peceño et al., 2021; Schützenhofer et al., 2022; Tazi et al., 2021), % materials reused (Bertin et al., 2020; IDEAL&CO Explore BV, n.d.; Medina and Fu, 2021), % circular inflow (Ellen MacArthur Foundation, 2015; WBCSD et al., n.d.; Zhang et al., 2021), and % circular outflow (Ellen MacArthur Foundation, 2015; WBCSD et al., n.d.; Zhang et al., 2021). A clear relationship between the 10R framework and several of these indicators is evident, as several indicators measure the percentage of the material following the strategies proposed by the 10R framework (e.g. % materials incinerated with energy recovery, % materials recycled, % materials reused).

Moreover, some MFA indicators have been integrated into indexes.

Among the most relevant are the *material circularity indicator* (*MCI*) by Ellen MacArthur Foundation (2015), and the latest *% material circularity*, by WBCSD (2023). The above references integrate a series of indicators to propose an overall index. In the case of *MCI*, it considers six indicators, including virgin feedstock, unrecoverable waste, and utility factors. The end value of MCI is a score between 0 and 1, where 1 represents the most circular value. Similarly, the *% material circularity* proposed by WBCSD is comprised of three indicators, circular inflow, % recovery potential, and % actual recovery. This index gives the same priority to the % actual and % potential recoveries. As the end value is represented in percentage, it provides a score between 0 and 100. Both of these indexes (*MCI* and *% material circularity*) consider the reintegration of the material mass into the system, and penalise models with linear economy thinking.

However, neither of these indexes fully measures the hierarchy levels proposed by the 10R framework. This is key, as CE definition not only intends to eliminate waste as the above indexes propose, but also highlights the importance of prioritising the value retention of materials through superior circular strategies. Indeed, the strategies proposed by the 10R framework are constantly referenced within the indicators currently used, covering 22.37 % of the indicators currently used to assess the environmental performance of CE (Table 1). Moreover, material use and waste were ranked fourth and seventh, covering 10.45 % and 7.8 % of the indicators found, respectively. Hence, a substantial number of indicators currently proposed are directly related to MFA. Nonetheless, none of the identified indexes integrates the 10R strategies, material use and waste generation.

3. Research methods

3.1. Approach

The scope of this study is depicted in Fig. 2. It adopts a postpositivist view, where new knowledge comes from the gradual accumulation of previous theories, findings, and testing the significance of relationships (Fien, 2002). Moreover, systematic combining is chosen as the approach to address the development of the proposed indicators and indexes. Within this approach, empirical fieldwork, theoretical frameworks and case studies are matched in an iterative process, from which new theories are created (Dubois and Gadde, 2002). The procedure commences with a comprehensive literature review in which empirical world documents, theory documents and case studies were reviewed to identify current trends of research and identify existing indicators used as metrics for CE environmental assessment (Muñoz et al., 2023b). Based on the findings of this review, a set of indicators based on MFA were identified as the most referenced to represent CE environmental performance. The key topics identified are related to the 10R framework, material use, and waste generation. Moreover, the analytic hierarchy process (AHP) was among the most referenced methods currently used in environmental performance methodologies. A description of these follows.

3.2. Analytic hierarchy process (multiple criteria decision making)

MCDM is a generic term for all methods that are used to make decisions according to people's preferences, in cases when there is more than one conflicting criterion (Ho, 2008; Mardani et al., 2015). MCDM aims to rank alternatives based on preference judgements made from defined criteria (Deng et al., 2011). A great variety of MCDM techniques have been proposed around the globe. However, the Analytic Hierarchy Process (AHP) is often referenced among the most used MCDM techniques (dos Santos Gonçalves and Campos, 2022; Mardani et al., 2015). AHP implements the fundamental scale to arrange the factors that are important for a decision, in a hierarchical structure descending from an overall goal (objective), to criteria, sub-criteria, and decision alternatives in successive levels (see Fig. 3) (Saaty, 1990). With the fundamental scale (Table 2), compared elements were related using a nine-point scale of comparison.

This study aims to use the AHP and the fundamental scale are relate it to the most cited indicators currently used based on MFA. Moreover, five case studies are generated as a validation method of the proposed approach.

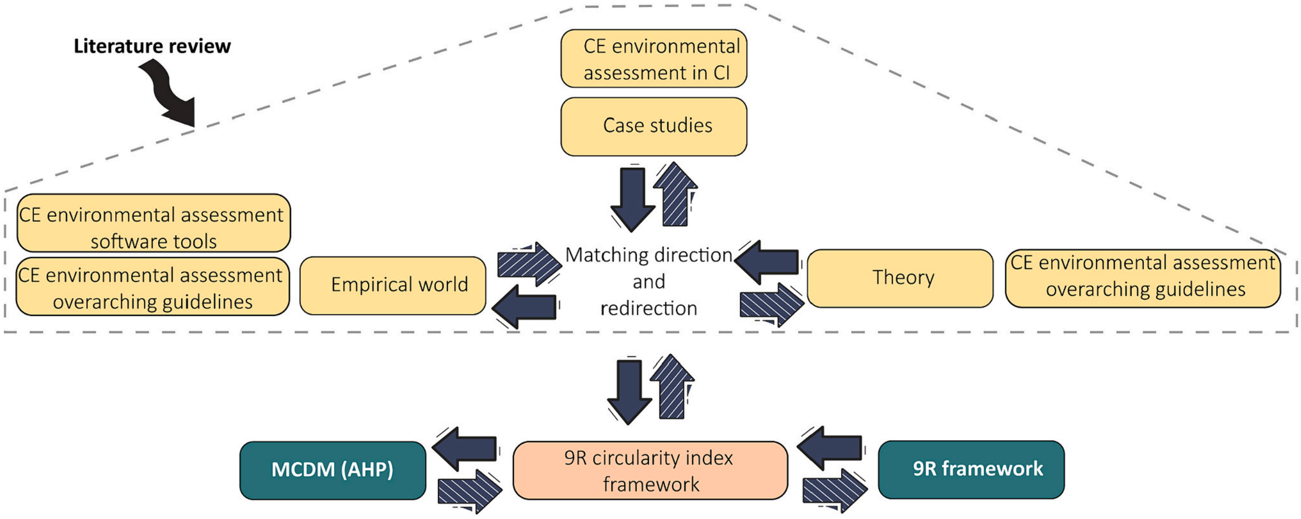


Fig. 2. Research design
Note: CE = circular economy, CI = construction industry, MCDM = multiple criteria decision making, AHP = analytic hierarchy process.

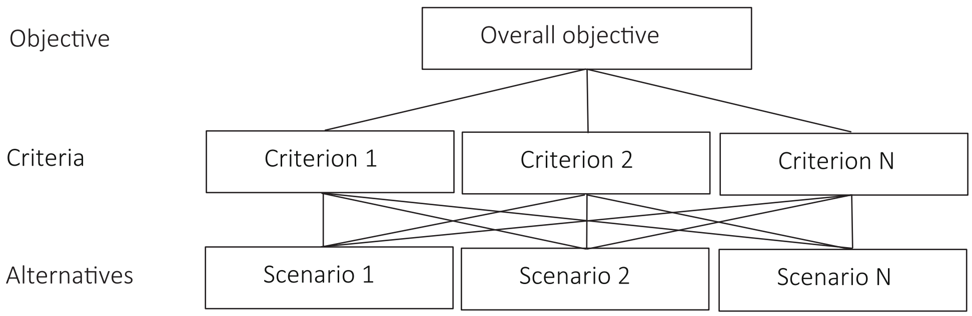


Fig. 3. The hierarchy model structure Adapted from Saaty (1990).

Table 2
The AHP fundamental scale. Adapted from Saaty (1990).

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favour one activity over another
5	Essential of strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgment	When compromise is needed

4. Results

4.1. Developing the 9R circularity index

This study proposes a set of indexes and indicators that consider the hierarchy levels of the 10R framework, as depicted in Fig. 4. Only the refuse strategy from the 10R framework is not considered. That is, the refuse strategy proposes to make product use redundant, which is out of the scope of an MFA of a specific material/product. Indeed, the refuse strategy aims to be used at a higher level, where two materials/products are already assessed, and the most environmentally friendly option needs to be chosen. In these cases, the 9R circularity indexes from two similar materials/products can be used. For instance, based on the 9R circularity scores of window panel type 1 and window panel type 2 presented in Table 16, the window panel type 1 should be refused.

Aside from the refuse strategy, the 9R strategies, or 9R framework — excluding refuse — (Fig. 1), can be considered within the defined system boundary of an MFA of a specific material/product. Indeed, each of the remaining nine strategies aims to increase the value retention of the material assessed through an MFA perspective.

Based on the 9R framework, the overall index proposed here is termed the *9R circularity index*. Similar to the material circularity indicator (MCI) (see Muñoz et al. (2023b) for details), the *9R circularity index* has a score range between 100 and 0, in which a higher value indicates a more circular product. Moreover, the *9R circularity index* oversees both potential and actual indicators. This approach is taken from the *% material circularity*, where the actual and potential impacts are integrated through a weighted average between them (WBCSD, 2023). Hence, the *9R circularity index* will be the integration of the *9R actual index* and *9R potential index*, while the *closed-loop circularity index* will be comprised of the weighted average between the *actual closed-loop index* and *potential closed-loop index* (see Fig. 4).

The *9R actual index* and *9R potential index* are comprised of the rethink and reduce strategies, and their respective *closed-loop index*. The closed-loop index's primary objective is to convey the extent of material recirculation within the defined system boundary of analysis, giving precedence to the 9R framework hierarchy. Therefore, this index integrates the following strategies: reuse, repair, refurbish, remanufacture, repurpose, recycle, recover, and virgin material use (in case of actual indexes), or landfill (in case of potential indexes).

The landfill indicator, used for the potential assessment, may be replaced by the virgin material use indicator, where the scope of the assessment is limited to upfront life cycle stages. The upfront life cycle

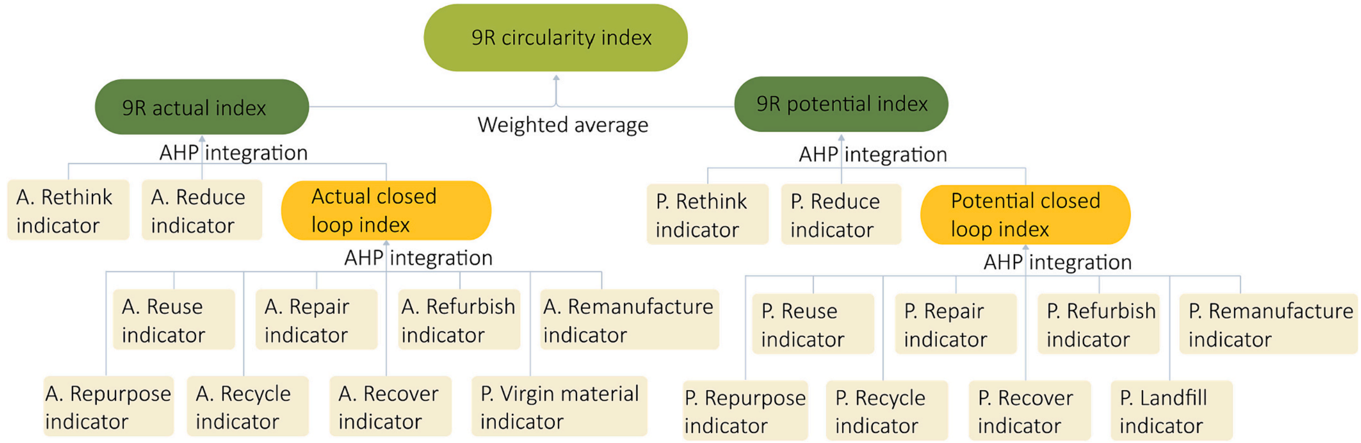


Fig. 4. 9R circularity index breakdown
Note: A = Actual, P = Potential, Landfill indicator can be modified with the virgin material use indicator if the scope of the assessment is limited to the upfront life cycle stages.

Table 3
Pairwise comparison for rethink strategy.

	Reduce	Reused	Repaired	Refurbished	Remanufactured	Repurposed	Recycled	Recovered
Rethink	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00

stages are the phases before the material is used, which are often comprised of the manufacturing, transportation and installation phases (WorldGBC, 2019).

To calculate the *9R actual* and *9R potential* indexes, the presented indicators are integrated through the AHP fundamental scale (Table 2). The weighting approach in this context involves prioritising certain indicators over others, following the 9R hierarchy. Landfilling and virgin material use, being non-circular, are assigned a weight of 0, indicating that they should not be prioritised. As for the remaining nine indicators, their hierarchy levels in the 9R framework are directly translated into the AHP fundamental scale. Hence, the comparison between strategies is matched to the fundamental scale, where the highest strategy (Rethink) scores nine against the lowest strategy (Recovered). By translating the fundamental scale to the 9R hierarchy, this approach eliminates the criteria weights subjectivity, as no external preferences are considered, nor are expert judgements used to create this index. To clarify this, the pairwise comparison of the Rethink indicator against the other indicators is tabulated in Table 3.

After conducting the pairwise comparisons, an Analytic Hierarchy Process (AHP) matrix is generated. The verification of matrix consistency complies with the following criteria:

$\lambda_{max} = 9.428$
Consistency index: 0.053
Ratio index for 9 variables: 1.45
Consistency ratio: 0.037

These consistency measures indicate that the AHP matrix is reliable for further analysis and decision making. The low consistency index and consistency ratio suggest that the pairwise comparisons were adequately consistent and free from significant biases. This validates the integrity of the decision-making process and enhances the credibility of the results obtained through the AHP framework.

The indicators and criteria weights to measure the 9R circularity index are presented in Table 4. 22 indicators are defined considering the 9R framework, landfilling, and virgin material use. Indeed, actual and potential indicators are defined, where the actual indicators measure how the material/product was generated, while the potential measures the possible end-of-life scenarios that may be achieved. The rethink and reduce scores are determined by comparisons against industry averages. As these values might not always be known, the industry average's predefined value is 0, which does not change the overall 9R circularity index score.

Moreover, the *9R circularity index* bottom-up approach can be further extended to any level, e.g., materials, products, offices, buildings, organisations, cities, regions, countries, and globally. To do so, the functional units must relate each lower level *9R circularity index* to its higher level, and the weighted average should be executed as illustrated in Fig. 5. This approach can be repeated until the desired level is achieved. In the case of an organisation, the weighted average of all products used within the organisation's structure should be considered.

Table 4
9R indicators and criteria weights.

Indicator	Description	Criteria weight
Rethink	Factor for product use intensity from −1 to 1. where 0 is industry average, −1 product use intensity is less than half or more, and 1 product is used at all possible time. The *actual rethink* relates to the manufacturing facilities use intensity, while the *potential rethink* relates to the end-product use intensity potential considered in the design phases.	30.70
Reduce	Efficiency of product manufacture from −1 to 1. where 0 is industry average, −1 double or more of the industry average materials are needed, and 1 no materials are needed. The *actual reduce* relates to how many material resources were used in the manufacturing process, while the *potential reduce* relates to the maximum potential efficiency in material resources needed in the manufacturing process.	21.82
Reused	Total material reused expressed in functional unit. The *actual reused* relates to how much material was reused to create the material/product, while the *potential reuse* relates to how much material/product is possible to be reused based on the design constraints (connections types, disassembly potential, etc).	15.43
Repaired	Total material repaired expressed in functional unit. The *actual repaired* relates to how much material was repaired to create the material/product, while the *potential repair* relates to how much material/product is possible to be repaired based on the design constraints.	10.89
Refurbished	Total material refurbished expressed in functional unit. The *actual refurbished* relates to how much material was refurbished to create the material/product, while the *potential refurbish* relates to how much material/product is possible to be refurbished based on the design constraints.	7.64
Remanufactured	Total material remanufactured expressed in functional unit. The *actual remanufactured* relates to how much material was remanufactured to create the material/product, while the *potential remanufacture* relates to how much material/product is possible to be remanufactured based on the design constraints.	5.33
Repurposed	Total material repurposed expressed in functional unit. The *actual repurposed* relates to how much material was repurposed to create the material/product, while the *potential repurpose* relates to how much material/product is possible to be repurposed based on the design constraints.	3.7
Recycled	Total material recycled expressed in functional unit. The *actual recycled* relates to how much material was recycled to create the material/product, while the *potential recycled* relates to how much material/product is possible to be recycled based on the design constraints.	2.59
Recovered	Total material recovered expressed in functional unit. The *actual recovered* relates to how much material was recovered to create the material/product, while the *potential recovered* relates to how much material/product is possible to be repurposed based on the design constraints.	1.89
Landfill	Total material landfilled expressed in functional unit. Relates to how much material/product is likely to be landfilled based on the design constraints.	0
Virgin material	Total virgin material sourced expressed in functional unit. The *actual virgin material* relates to how much material was used to create the material/product. If the scope of the assessment is limited to the upfront life cycle stages, the *potential virgin material* relates to how much virgin material/product is likely to be used based on the design constraints.	0

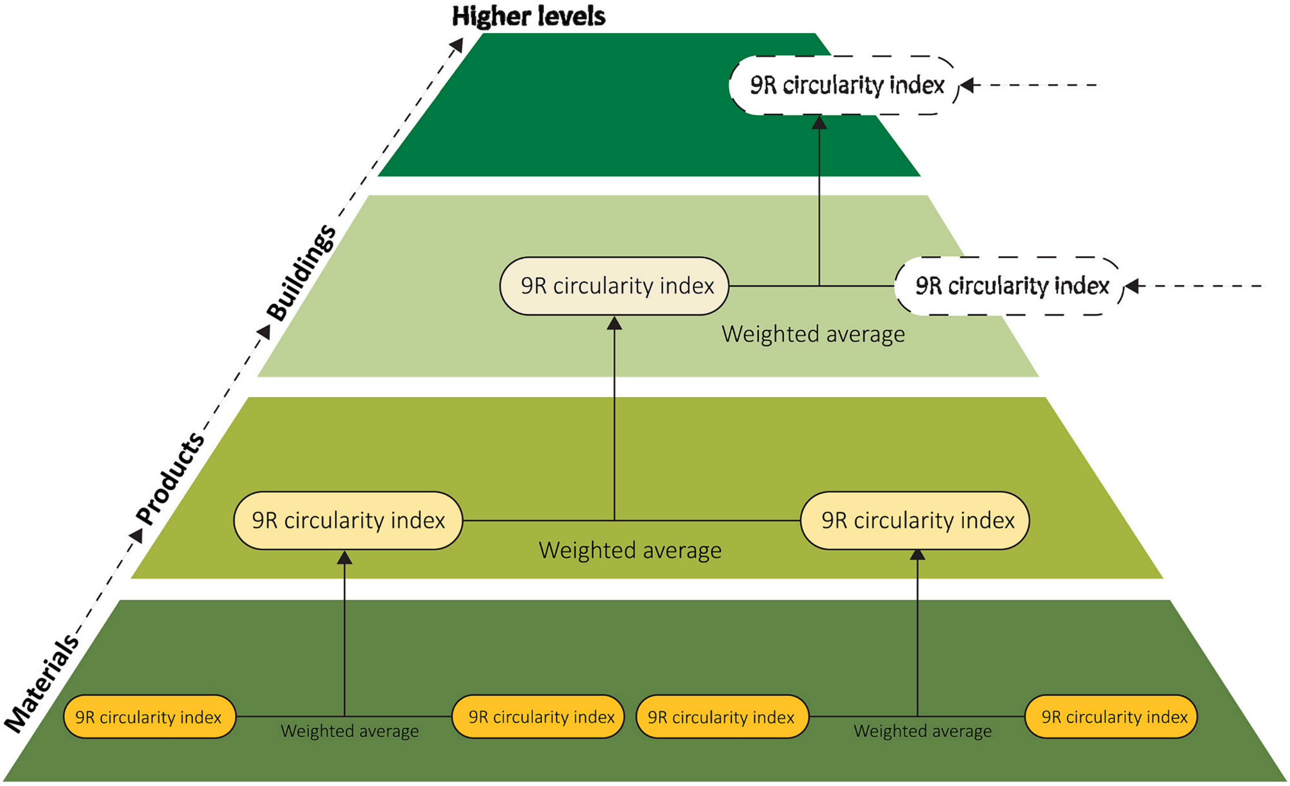


Fig. 5. 9R circularity index bottom-up approach
Note: Example illustrates upper-levels composed of two lower-levels. Depending on the scope, there might be different ratios between levels.

4.2. Calculating the 9R circularity index

A step-by-step approach is presented for the index calculation, following the steps below.

Step 1: Define the levels of assessment and the elements composing each level

The *9R circularity index* bottom-up approach begins at the material level; its values can be integrated to produce a higher-level score (see Fig. 5). To do so, the definition of all the levels and the elements composing each level within the system boundary must be generated.

Step 2: Define functional units considering higher levels within the system boundary.

The end-user must provide specific material values in functional units for the strategies occurring within the system boundary, as defined by the LCA's ISO standards (ISO, 2006). Therefore, when evaluating these indicators, it is essential to adopt the common units used in current practices, such as in environmental product declarations. The use of functional units is designed to streamline analysis and enable the comparison of products in the same category. For example, concrete is commonly measured in m^3, whereas steel is measured in kg. When selecting the functional unit, the relationship between each level of assessment must be carefully considered, as it will define how to integrate the results from lower levels into higher levels.

Step 3: Measure the actual 9R strategies used to create the materials and products within the system boundary. Calculate the actual closed-loop index and 9R actual index of the first selected material.

To measure the *9R actual index* (see Fig. 4), the measurement of the actual indicators (Table 4) must be based on how the materials and products have been manufactured. The actual values should be of lower hierarchy as the potential values, as the ideal scenario. Depending on the system's boundary level, the *actual rethink* indicator may have variations.

Based on Steps 1–3, the calculation of the *actual closed-loop index* can be done. When measuring the closed-loop indexes, the end-user must enter material values expressed in functional units. Each indicator must be normalised by the total material values entered. This is necessary to consider the materials landfilled and virgin materials used. The normalised material values should then be multiplied by the criteria weight. Lastly, the value should be divided by the maximum score of the entire criteria weight (0.67947) to represent the value in a score from 0 to 100 (including rethink and reduce criteria). The closed-loop index value ranges from 0 in a fully linear model (where all materials end up in a landfill), to 22.71, where all materials are reused. Following these steps and considering the actual 9R strategies used to create the materials and products within the system boundary, the *actual closed-loop* index can be calculated.

The assessment of the actual rethink and *actual reduce* indicators should be conducted by calculating the product of the criteria weight and the input from end-user indicators. Specifically, the rethink indicator pertains to the relative intensity of utilisation in manufacturing facilities, juxtaposed with the industry average. This indicator aims to maximise the facilities' use, consequently reducing the number of facilities needed to produce the same quantities of materials. Moreover, the *actual reduce* indicator relates to how many material resources were used in the manufacturing process, compared to the industry average. Lastly, the summation of the *actual closed-loop index*, *actual rethink,* and *actual reduce* indicators generate the *9R actual index.*

Step 4: Identify the potential 9R strategies within the system boundary. Calculate the potential closed-loop index and 9R potential index of the first selected material.

The connection types used within the materials must be defined. This will limit their 9R strategy potential. Exploring the connection types and the product's end-of-life strategies potential is key to measuring the *potential closed-loop index*. Depending on the system boundary level, this potential may be higher or lower, as additional connection restrictions may be defined as higher levels are reviewed. Based on this analysis, the *potential closed-loop index* should be measured (refer to Step 3).

Moreover, the *potential rethink* and *potential reduce* indicators should be measured by multiplying the criteria weight by the end-user indicators input. The *potential rethink* indicator relates to the product use intensity potential considered in the design phases. The *potential rethink* indicator should only be considered if the use intensity increase is considered in the design stages (refer to Step 3 in Section 4.3 as an example). This approach aims to incentivise *rethink* in the design stages. Moreover, the *potential reduce* indicator relates to the maximum potential efficiency in using the material resources needed in the manufacturing process. The summation of the *potential closed-loop index*, *potential rethink,* and *potential reduce* indicators generates the *9R potential index*.

Step 5: Calculate the 9R circularity index of the first selected material.

Beginning at the material level, the weighted average between the *9R actual index* and *9R potential index* of each material will result in the material's overall *9R circularity index* (Fig. 4). Moreover, as an optional step, the *closed-loop circularity index* can also be measured as the weighted average between the *actual closed-loop index* and the *potential closed-loop index*.

Step 6 Repeat Steps 3–5 to calculate the 9R circularity index for all materials within the system boundary.

Steps 3 to 5 must be generated for all the materials within the system boundary. This will result in 9R circularity index scores for each of the materials within the scope of the assessment.

Step 7: Calculate the 9R circularity index for all levels within the system boundary.

The weighted average of the *9R circularity indexes* of a lower level can be integrated to measure a higher level. This can be repeated until the indexes at all levels are defined within the system boundary (e.g., metal, plastic, and rubber *9R circularity indexes* weighted average can compose a bicycle *9R circularity index*). The weighted average should consider the quantities required in the lower level to comprise a higher level (see Fig. 5). Functional units must guide this process. As higher levels are achieved, the index scores may have variations that should be considered, as differences may be generated in its indicators (variations in connection types and rethink potentials).

4.3. Validating the practicality of the 9R circularity index

To validate the practicality of using the 9R circularity index, five cases will be tested with the proposed approach and based on the recommended steps at any CE level. These case studies follow the steps defined in Section 4.2. Using the Microsoft Excel tool as guide is highly recommended while reading the following validation (Muñoz et al., 2023a).

Step 1: Define levels of assessment and elements composing each level.

The first case comprises the assessment of two materials, followed by a product, a building and finally, a city. For this illustration, a city is comprised of a group of buildings, a building by a group of products, and a product by a group of materials (The same principle could be used for organisations, in which the group of products used within the company will result in the organisation's score).

For illustrative purposes, the materials selected for this case study are aluminium and glass. The product is a $1m^2$ glass window with an aluminium frame. The building is limited to a façade comprised of 10 x $1m^2$ window panels, and the city is comprised of 10 building façades. In reality, all elements within each level should be measured (for buildings, elements should consider structural products, walls, insulation products, services, etc.).

Step 2: Define functional units considering higher levels within the system boundary.

To measure the illustrative city's performance, the functional units of each sub-level should be related to the upper level. In this case, for aluminium and glass materials, the common functional unit is kg. Moreover, as they are used in a window frame, a common functional unit for the window frame could be kg/m^2, or kg/window panel. To simplify the case, the window panel measures is equivalent to $1m^2$. Moreover, the functional unit of kg/window panel is used to relate the material level to the product level. 5 kg of aluminium and 10 kg of glass will be needed in each window panel. Similarly, 10 window panels comprise the building façade, and the city is comprised of 10 building façades.

Step 3: Measure the actual 9R strategies used to create the materials and products within the system boundary. Calculate the *actual closed-loop index* and *9R actual index* of the first selected material.

Aluminium has been chosen as it has great 9R strategy potential. If the material is protected from corrosion, e.g., zinc coating, the product's life expectancy can be extended for very long periods. Moreover, it is a lightweight and high-strength material in which any of the closed-loop strategies may occur (Fig. 4). In this case, the aluminium frames implemented in glass windows were assessed. The material *actual closed-loop index*, which relates to how the material was created, it is assumed that none of the material has used the strategies at the higher level. However, 40 % (2 kg per window panel) is assumed to be created with recycled content, while the other 60 % (3 kg per window panel) comes from virgin material sources.

The *actual rethink* and *actual reduce* indicators should be measured by multiplying the criteria weight by the end-user indicators input. The *actual rethink* indicator relates to the manufacturing facilities' use intensity, relating it to the industry average. For this case, the use intensity is the industry average, giving a 0 score for *actual rethink*. Moreover, the *actual reduce* indicator, relates to how many material resources were used in the manufacturing process. In this case, the efficiency of product manufacturing is assumed to be 10 % above the industry average (10 % less natural resources are input for every kg of aluminium produced). Based on these values, the actual closed-loop index and actual 9R index for aluminium used in a window panel are presented below in Table 5 and Table 6, respectively.

Table 5
Aluminium in window panel actual closed-loop index.

Indicator	Criteria weight %	Material in kg/ window panel	Normalised material	Score	Normalised Score
Reused	15.43		0.00	0.000	0.000
Repaired	10.89		0.00	0.000	0.000
Refurbished	7.64		0.00	0.000	0.000
Remanufactured	5.33		0.00	0.000	0.000
Repurposed	3.70		0.00	0.000	0.000
Recycled	2.59	2	0.40	1.038	1.527
Recovered	1.89		0.00	0.000	0.000
Virgin material	0.00	3	0.60	0.000	0.000
	Total	5	**Actual closed-loop index**		1.527

Table 6
Aluminium in window panel actual 9R index.

Index/indicator	Criteria weight %	Factors	Score	Normalised Score
Actual closed-loop index				1.527
Rethink	30.70	0	0.000	0.000
Reduce	21.82	0.1	2.182	3.211
		Actual 9R index		4.739

Step 4: Identify the potential 9R strategies within the system boundary. Calculate the *potential closed-loop index* and *9R potential index* of the first selected material.

This potential must be based on material property limitations and current technological advancements. Regarding the aluminium *potential closed-loop index*, it is assumed that aluminium panels do not have any permanent joints or sealants, resulting in a full (100 %) *potential reuse* for the aluminium material if a glass frame is broken or a panel needs to be replaced. Based on this potential, the *potential closed-loop* index can be measured.

This case provides a great example of the rethink variations that different levels may imply. For instance, at the material and product level, little information would be available to identify the final factor use intensity potential of each material, making a *potential rethink* of 0. At the product level, a window panel will always have the same use intensity, as it is a passive element that is used all the time during the building use stage, making a *potential rethink* of 0. However, at the building level, the potential of use intensity could be increased by sharing the use of the building, or sections of the building, (e.,g, meeting rooms as social areas on the weekends) for various purposes at different times of the day or week. For instance, assuming the buildings are offices, the typical use would be from Monday to Friday 7 am-6 pm. If the building is adapted to be used for other purposes on weekends or during night, this will increase the use intensity potential, consequently increasing the rethink potential of all the sublevels that are used to create the building. However, the *potential rethink* in buildings, related to the use intensity potential, should only be accounted for if the use intensity is considered within the design stages of the building. This approach aims to incentivise a rethink of potential thinking in the design stages. For this case, no use intensity strategy was considered in the design stage, leaving the factor as 0.

Moreover, it is assumed that the product efficiency related to the *potential reduce indicator* could be optimised by up to 30 % of the current industry average (30 % less natural resources are input for every kg of aluminium produced). Based on these values, the scoring of the aluminium is presented below (Tables 7 and 8):

Table 7
Aluminium in window panel potential closed-loop index.

Indicator	Criteria weight %	Material in kg/ window panel	Normalised material	Score	Normalised Score
Reuse	15.43	5	1.00	15.432	22.712
Repair	10.89		0.00	0.000	0.000
Refurbish	7.64		0.00	0.000	0.000
Remanufacture	5.33		0.00	0.000	0.000
Repurpose	3.70		0.00	0.000	0.000
Recycle	2.59		0.00	0.000	0.000
Recover	1.89		0.00	0.000	0.000
Landfill	0.00		0.00	0.000	0.000
	Total	5	**Potential closed-loop index**		**22.712**

Table 8
Aluminium in window panel potential 9R index.

Index/indicator	Criteria weight %	Factors	Score	Normalised Score
Closed-loop index				0.227
Rethink	30.70	0	0.000	0.000
Reduce	21.82	0.3	6.546	9.634
		Potential 9R index		**32.346**

Step 5: Calculate the *9R circularity index* of the first selected material.

The *9R circularity index and closed-loop circularity index* can be calculated based on the weighted average of the *actual* and *potential* index scores. In this case study, the first material to be assessed is aluminium. The aluminium *closed-loop circularity index* score is 12.12, while the aluminium *9R circularity index* is 18.54, as shown in Table 9.

Step 6: Repeat Steps 3–5 to calculate the *9R circularity index* for all materials within the system boundary.

The same approach from the aluminium scoring must be followed with the glass implemented in the window panel. In this case, for the glass *actual closed-loop index*, 30 % of the material is assumed to come from recycled sources, and 70 % from virgin materials (Table 10). Moreover, for the glass *9R actual index*, similarly to aluminium, the factory use intensity is the industry average, giving a 0 score for *actual rethink* (a façade element can not have a higher or lower use intensity, and no strategy has been defined at the building level at the design stage). Furthermore, the efficiency of material consumption in the manufacturing process is assumed to be 20 % above the industry average (*actual reduce* indicator). Table 11 presents the glass *actual 9R index* score.

Additionally, glass has a tremendous 9R strategy potential. For the *potential closed-loop index* (Table 12), as there are no permanent joints, nor between the materials inside the window panel (aluminium and glass), neither between the materials composing the window panels (e.g., window frames are not welded or glued together); there is a full potential for material recovery, with 100 % *potential reuse*. Moreover, for

Table 9
Aluminium in window panel closed-loop circularity index and 9R circularity index.

Actual closed-loop index	Potential closed-loop index	**Closed-loop circularity index**
1.527	22.71	12.12

Actual 9R index	Potential 9R index	**9R circularity index**
4.739	32.35	18.54

Table 10
Glass in window panel actual closed-loop index.

Indicator	Criteria weight %	Material in kg/ window panel	Normalised material	Score	Normalised Score
Reused	15.43		0.00	0.000	0.000
Repaired	10.89		0.00	0.000	0.000
Refurbished	7.64		0.00	0.000	0.000
Remanufactured	5.33		0.00	0.000	0.000
Repurposed	3.70		0.00	0.000	0.000
Recycled	2.59	3	0.30	0.778	1.146
Recovered	1.89		0.00	0.000	0.000
Virgin material	0.00	7	0.70	0.000	0.000
	Total	10	**Actual closed-loop index**		1.146

Table 11
Glass in window panel actual 9R index.

Index/indicator	Criteria weight %	Factors	Score	Normalised Score
Actual closed-loop index				1.146
Rethink	30.70		0.000	0.000
Reduce	21.82	0.2	4.364	6.423
		Actual 9R index		7.568

Table 12
Glass in window panel potential closed-loop index.

Indicator	Criteria weight %	Material in kg/ window panel	Normalised material	Score	Normalised Score
Reuse	15.43	10	1.00	15.432	22.712
Repair	10.89		0.00	0.000	0.000
Refurbish	7.64		0.00	0.000	0.000
Remanufacture	5.33		0.00	0.000	0.000
Repurpose	3.70		0.00	0.000	0.000
Recycle	2.59		0.00	0.000	0.000
Recover	1.89		0.00	0.000	0.000
Landfill	0.00		0.00	0.000	0.000
	Total	10	**Potential closed-loop index**		22.712

the *9R potential index* (Table 13), product manufacturing potential is assumed to be increased by up to 30 % of the current industry average (*potential reduce* indicator). Based on these assumptions, the glass *closed-loop circularity index* and *9R circularity index* scores are presented in Table 14.

In reality, glass in industry average window panels may not be fully reused due to permanent sealants between the aluminium frame and the glass. Hence, the potential should be decreased until the maximum level is achievable, e.g., if the glass needs to be broken and can only be recycled, the potential indicator should specify this. Likewise, if the assessment is of a material that cannot be recycled, the potential index scores should represent this.

Table 13
Glass in window panel potential 9R index.

Index/indicator	Criteria weight %	Factors	Score	Normalised Score
Potential closed-loop index				22.712
Rethink	30.70	0	0.000	0.000
Reduce	21.82	0.3	6.546	9.634
		Potential 9R index		32.346

Table 14
Glass indexes scores.

Actual closed-loop index	Potential closed-loop index	**Closed-loop circularity index**
1.15	22.71	11.93

Actual 9R index	Potential 9R index	**9R circularity index**
7.57	32.35	19.96

Step 7: Calculate the *9R circularity index* for all levels within the system boundary.

Once all the material's 9R circularity indexes are measured (aluminium and glass for this example), the index score assessment can be increased to a higher level. In this model, the next level is at the product level, namely the window panel. The product scoring can be measured by generating the weighted average of the materials that compose the product. During the product scoring, the ratio of materials should be considered. In this case, when scoring the window panel 9R circularity index, the weight of aluminium is lower against the glass, as only 5 kg of aluminium is needed against 10 kg of glass for each panel. The window panel has a 0.12 *closed-loop circularity* index score, and a 0.195 *9R circularity index score*, as stated in Table 15.

Following this approach, the score assessment can be increased to a higher level (buildings in this example). The index assessment of the building can be done by calculating the weighted average from all the products that compose the buildings. In this example, the entire building assessment is limited to the window panels in the façade. Hence, the scoring is produced as stated in Table 16. Lastly, the city example is limited to 10 buildings, as presented in Table 17. The weighted average should be considered at all levels, as shown in Table 15.

In reality, all products that compose the building should be measured and considered within the building index score through weighted averages based on the functional units required per building (Table 15 as an example). Similarly, the city assessment should consider variations within buildings.

Table 15
Window panel 9R circularity index.

Materials and product	Kg/window panel	Closed-loop circularity index	9R circularity index
Aluminium	5	12.12	18.54
Glass	10	11.93	19.96
Window panel type 1	15	11.99	19.49

Table 16
Building 9R circularity index.

Products and building	Window panels/ building	Closed-loop circularity index	9R circularity index
Window panel type 1	6	11.99	19.49
Window panel type 2	4	9.00	30.50
Building type 1	10	10.79	23.89

Note: Window panel type 1 calculation is presented in Table 15. Windows panel type 2 is modified as an illustration.

Table 17
City 9R circularity index.

Buildings and city	Building/ city	Closed-loop circularity index	9R circularity index
Building type 1	6	10.79	23.89
Building type 2	4	14.50	27.80
City	10	12.27	25.45

Note: Building type 1 calculation is presented in Table 17. Building type 2 is modified as an illustration.

Table 18
Comparison of CE bottom-up approaches.

	9R circularity index	MCI	% material circularity
Scenario 1	12.12	0.73	40.00
Scenario 2	15.90	0.73	40.00
Scenario 3	20.71	0.73	53.33

As further validation for the proposed approach, a comparison against currently used indicators is presented in Table 18. Tree scenarios are generated:

- Scenario 1: Actual (60 % virgin material, 40 % recycled), Potential (100 % reused).
- Scenario 2: Actual (60 % virgin material, 40 % reused), Potential (100 % reused), and
- Scenario 3: Actual (60 % repaired, 40 % recycled), Potential (100 % reused).

Findings demonstrate that the hierarchy proposition defined in the 9R circularity index plays a vital role in differentiating similar scenarios. Indeed, a clear ranking between the three defined scenarios can only be achieved through the proposed approach.

5. Discussion

The approach presented here is based on a comprehensive review generated on both academic and grey literature indicators currently used to measure the environmental assessment of CE. The findings presented here integrate several approaches currently used, namely the MCI index, the % material circularity index, the 9R framework, and the Analytic Hierarchy Process (AHP) multi-criteria decision-making (MCDM) method. Through the integration of the AHP fundamental scale against the 9R framework, a quantitative weighting has been set for a group of indicators measuring both the actual and potential environmental performance of the 9R framework, the virgin materials used, and the landfill potential.

Two indexes are generated based on this approach, namely the *closed-loop circularity index* and *9R circularity index*. The *closed-loop circularity index* measures indicators related to creating a closed-loop model, where materials are recirculated through the system, reducing (and ideally eliminating) landfilling and the need for new virgin materials. Moreover, the *closed-loop circularity index* is then integrated with two indicators (rethink and reduce) to create the *9R circularity index*. The presented indexes not only measure CE models; they differentiate the best strategies following the hierarchy proposed by the 9R framework. As the approach presented here considers both the actual and potential indicators, these indexes could help differentiate best practices, by representing more comprehensively the different savings the 9R strategies may bring to the economy. Moreover, the bottom-up approach brings the possibility of measuring the *9R circularity index* at any level and system boundary. To facilitate its use, the authors have generated a free-to-use iterative tool to measure the proposed indexes (Muñoz et al., 2023a).

The novelty of the proposed indicators and indexes is based on the integration of the CE definition and the 9R strategies, which has been an interaction neglected in current CE assessment approaches. Even though the refuse strategy is not included within the indexes assessment, the *9R circularity index* and *closed-loop circularity index* can play a crucial role when choosing between two products, as the refuse strategy aims. For instance, based on the 9R circularity index scores of window panel type 1 and window panel type 2 presented in Table 16, window panel type 1 should be refused.

The *9R circularity index* and *closed-loop circularity index* consider the virgin material use and potential landfill indicators. With the integration of these last indicators, the assessment goes beyond the 9R strategies to consider a broader spectrum of the CE definition, specifically material sourcing and waste elimination.

As another innovative feature of the proposed index, though the example presented in this paper is oriented to measure a city index score with a bias towards the building industry, these indicators and indexes can be applied at any level and industry following a bottom-up approach. Indeed, they have a great potential to measure the environmental performance of organisations. The potential at this level is not only to measure and present the products generated by the company (similar to current food health scorings, EPDs and MCI scores); additionally, these indexes can be used to measure the entire organisation's performance. These assessments can be done gradually by defining different system boundaries (e.g., operational stage products used in a specific office, then all offices, then including construction materials used to create the offices).

Additionally, companies implementing the product-as-a-service model would greatly benefit from considering this index. Indeed, the strategies that give the highest scores will require a transition to this type of model, where organisations take responsibility for their product operational and end-of-life phases to reintroduce them within new products, implementing strategies such as reuse, repair, and remanufacture. Moreover, this index also has implications for organisations that consider material passports, design for assembly and disassembly, and/or right-to-repair principles. All these principles sustain higher potential index scoring, as each of them increases the actual and potential material recovery.

Indeed, the approach presented in this paper greatly facilitates the distinction between traditional companies and companies that responsibly manage their products during their entire life cycle, considering their products' end-of-life potential. The index presented in this paper captures a rich definition of a CE, stepping aside from current indicators that give a similar scoring to organisations that implement any CE strategy, without representing the different benefits that higher strategies may bring. Likewise, the index scoring has been designed based on current approaches, with the scoring ranging from 0 to 100 for the 9R circularity index, similar to the MCI. The use of this basic scoring range generates simple results that can be used to inform decision-making for end-users, who can easily identify more sustainable options.

This approach empowers both experts and non-experts in CE reasoning. Experts can conduct in-depth analyses of manufacturing processes and assess the 9R circularity index for any product, building, or organisation. These results can then be certified by third parties and shared with non-experts. Armed with this information, non-experts can leverage the certified assessments to make informed decisions when comparing similar products or services.

Moreover, the proposed Excel tool greatly facilitates the *9R circularity index* bottom-up approach (Muñoz et al., 2023a). Indeed, once the actual and potential material scenarios to be assessed are defined, the translation of these scenarios can be done in seconds to the tool, which will provide the 9R circularity index score. This step can be replicated in all materials within the scope with ease. Then, the integration into a higher level (product) can be computed by simply aggregating the material scores using the weighted averages.

5.1. Limitations and future areas for research

The index presented here merely focuses on material flow analysis. Future explorations should consider how to integrate this index with other environmental impacts such as greenhouse gas emissions, water consumption, and energy consumption. It is reasonable to expect that a higher 9R circularity index score would represent environmental savings in other environmental impact categories when most parameters between models are maintained. However, this might not always be the case, as argued by Muñoz et al. (2023b). For instance, if the recovery of materials implies great transportation distances based on diesel fuel vehicles, the greenhouse gas emissions generated by a remanufacturing model might not necessarily be lower compared to a more linear model.

Moreover, the proposed approach is oriented to the technical cycle rather than the biological one. The end-of-life strategies of the biological cycle are different, e.g., anaerobic digestion. Likewise, the approach presented here considers landfilling as a non-circular economy, non-differentiating if the assessment is of biodegradable materials or not. This limitation could be considered by integrating the proposed index with additional indicators such as the ones commonly proposed in LCA. Having stated this, several biological materials could be assessed with the proposed approach. For instance, timber structures may follow any of the potential scenarios considered in this model, including the reuse, remanufacturing and recovery of the materials after their use phase finalises. Moreover, even when considering biological materials, landfilling at their end-of-life is not ideal, as there are potential scenarios that may reintegrate them as part of a new cycle, e.g., replacing virgin material use, use as nutrients in agriculture or forest, and incineration with energy recovery.

Among the limitations of this paper's approach is the missing implications a CE model may have to step aside from a material flow perspective. Indeed, other environmental impact categories may significantly vary based on CE models. It must not be assumed that all other environmental impacts will be always reduced. The exploration of how to integrate the proposed indexes (representing the material flows) with LCA should be further explored to consider a full CE picture; one in which material values are maximised through closed-loop models, product life expectancy is improved through superior quality, energy is based on renewable sources, climate change is mitigated, social and economic implications are accounted, and all other human activities environmental impacts are reduced.

Lastly, an additional limitation identified in the proposed approach is regarding the life expectancy and quality parameters. Indeed, the approach presented here does not differentiate between products that may extend their use phase through superior quality designs. However, this limitation could be addressed with a complimentary LCA analysis with a predefined number of years to be assessed. The predefined number of years should consider the average life expectancy of products to create a model where more than one product cycle is achieved. For instance, for construction material cycles, it could be 200 years, while for short-term products such as electronics, it could be 20 years. An LCA analysis conducted on predefined timelines would differentiate models that are generating higher environmental impacts in the long term. Considering all the environmental implications of a closed-loop model for other environmental impact categories plays a vital role in achieving a more sustainable CE.

It is important to note that all the above limitations also apply to the currently used indexes, namely MCI and “% material circularity”. Indeed, these approaches only limit their approach to an MFA focused on waste elimination without identifying all the above limitations when doing that. The proposed approach here goes beyond current indexes. It not only defines an approach in which waste elimination is measured (as MCI and “% material circularity” currently do), but sets a scoring where value retention through superior strategies is rewarded. The approach presented here resolves the integration between three key topics currently used to assess CE: the 9R framework, material use and waste generation. It goes beyond by considering actual and potential material flow assessments, while defining a step-by-step framework that can be gradually adopted through smaller to higher scopes. Additionally, it identifies its weaknesses so future research can explore how to address them, something often neglected in the currently used CE indicators and indexes.

6. Conclusion

The primary contribution of this research paper lies in introducing a novel measurement system for Circular Economy (CE), designed to overcome the limitations and deficiencies inherent in existing metrics and indices. By encompassing the full spectrum of 9R strategies pertinent to CE, this system is adept at capturing various dimensions, thereby mitigating potential unintended consequences, notably the rebound effects often overlooked in current measures. The proposed approach resolves the repeated question of how to score the technical cycle of the Ellen Macarthur CE butterfly diagram, and its more extended version: the 9R framework.

From a theoretical standpoint, the methodologies proposed in this paper not only provide a fresh perspective but also enrich scholarly discourse on the adoption and quantification of CE practices. These approaches address the existing differentiation and fragmentation in the field, paving the way for a more unified and comprehensive understanding of CE measurement.

In practical terms, this paper serves as a valuable resource for practitioners and policymakers engaged in CE initiatives. By offering a robust framework for assessing the effectiveness of CE adoption, it empowers stakeholders to track progress across multiple environmental facets. This comprehensive monitoring tool is vital for developing and refining policies aimed at fostering a seamless transition towards a CE. Furthermore, the proposed measurement system highlights existing data gaps and encourages the exploration of new data streams, enabling authorities and organisations to gauge their progress in implementing CE principles more accurately.

CRediT authorship contribution statement

Santiago Muñoz: Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **M. Reza Hosseini:** Supervision, Writing – review & editing, Visualization. **Robert H. Crawford:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

ACE Hub, 2022. Measuring the Circular Economy: An Australian Perspective.
Adabre, M.A., Chan, A.P.C., Darko, A., Hosseini, M.R., 2023. Facilitating a transition to a circular economy in construction projects: intermediate theoretical models based on the theory of planned behaviour. Building Research & Information 51 (1), 85–104.
Ansanelli, G., Fiorentino, G., Tammaro, M., Zucaro, A., 2021. A life cycle assessment of a recovery process from end-of-life photovoltaic panels. Appl. Energy 290.
Backes, J.G., Del Rosario, P., Petrosa, D., Traverso, M., Hatzfeld, T., Günther, E., 2022. Building sector issues in about 100 years: end-of-life scenarios of carbon-reinforced concrete presented in the context of a life cycle assessment, focusing the carbon footprint. Process 10 (9).
Bertin, I., Mesnil, R., Jaeger, J.M., Feraille, A., Le Roy, R., 2020. A BIM-based framework and databank for reusing load-bearing structural elements. Sustainability 12 (8).
Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21 (3), 603–614.
Bocken, N.M.P., Olivetti, E.A., Cullen, J.M., Potting, J., Lifset, R., 2017. Taking the circularity to the next level: a special issue on the circular economy. Journal of Industrial Ecology 21 (3), 476–482.
Bonoli, A., Degli Esposti, A., Magrini, C., 2020. A case study of industrial symbiosis to reduce GHG emissions: performance analysis and LCA of asphalt concretes made with RAP aggregates and steel slags. Front. Mater. 7, 572955 https://doi.org/10.3389/fmats.
Brunner, P.H., Rechberger, H., 2016. Handbook of Material Flow Analysis.
Butković, L.L., Mihić, M., Sigmund, Z., 2021. Assessment methods for evaluating circular economy projects in construction: a review of available tools. Int. J. Constr. Manag. 1–10.
Cagno, E., Negri, M., Neri, A., Giambone, M., 2023. One framework to rule them all: an integrated, multi-level and scalable performance measurement framework of sustainability, circular economy and industrial symbiosis. Sustainable Production and Consumption 35, 55–71.
Calzolari, T., Genovese, A., Brint, A., 2022. Circular economy indicators for supply chains: a systematic literature review. Environmental and Sustainability Indicators 13, 100160.
Circle Economy Foundation, 2023. The Circularity Gap Report. https://www.circularity-gap.world/2023 (Accessed 14 November 2023).

Colangelo, F., Navarro, T.G., Farina, I., Petrillo, A., 2020. Comparative LCA of concrete with recycled aggregates: a circular economy mindset in Europe. Int. J. Life Cycle Assess. 25 (9), 1790–1804.

Cradle to Cradle Products Innovation Institute, 2021. Cradle to Cradle certified®Product Standard, Version 4.0 ed., p. 98.

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: the 61 indicators. J. Clean. Prod. 281, 124942.

Deng, Y., Chan, F.T.S., Wu, Y., Wang, D., 2011. A new linguistic MCDM method based on multiple-criterion data fusion. Expert Syst. Appl. 38 (6), 6985–6993.

Dubois, A., Gadde, L.-E., 2002. Systematic combining: an abductive approach to case research. J. Bus. Res. 55 (7), 553–560.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751.

Ellen MacArthur Foundation, 2015. Material Circularity Indicator (MCI).

Fien, J., 2002. Advancing sustainability in higher education: issues and opportunities for research. International journal of sustainability in higher education.

Fořt, J., Černý, R., 2020. Transition to circular economy in the construction industry: environmental aspects of waste brick recycling scenarios. Waste Manag. 118, 510–520.

Ghafoor, S., Hosseini, M.R., Kocaturk, T., Weiss, M., Barnett, M., 2023. The product-service system approach for housing in a circular economy: an integrative literature review. J. Clean. Prod. 403, 136845.

Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption 26, 172–186.

Ho, W., 2008. Integrated analytic hierarchy process and its applications – a literature review. European Journal of Operational Research 186 (1), 211–228.

IDEAL&CO Explore BV, n.d. Circularity calculator.

ISO, 2006. ISO 14044:2006, Environmental management - life cycle assessment - Requirements and guidelines. International Organization for Standardization.

ISO, 2017. ISO 21930:2017, Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services. International Organization for Standardization.

Jiménez-Rivero, A., García-Navarro, J., 2016. Indicators to measure the management performance of end-of-life gypsum: from deconstruction to production of recycled gypsum. Waste Biomass Valoriz. 7 (4), 913–927.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resources, Conservation and Recycling 127, 221–232.

Kirchherr, J., Yang, N.-H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour. Conserv. Recycl. 194, 107001.

Lachat, A., Mantalovas, K., Desbois, T., Yazoghli-Marzouk, O., Colas, A.S., Di Mino, G., Feraille, A., 2021. From buildings' end of life to aggregate recycling under a circular economic perspective: a comparative life cycle assessment case study. Sustainability 13 (17).

Mardani, A., Jusoh, A., Nor, K., Khalifah, Z., Zakwan, N., Valipour, A., 2015. Multiple criteria decision-making techniques and their applications–a review of the literature from 2000 to 2014. Economic research-Ekonomska istraživanja 28 (1), 516–571.

Martinho, V.J.P.D., 2021. Insights into circular economy indicators: emphasizing dimensions of sustainability. Environmental and Sustainability Indicators 10, 100119.

Matos, J., Martins, C., Simões, C.L., Simoes, R., 2023. Comparative analysis of micro level indicators for evaluating the progress towards a circular economy. Sustainable Production and Consumption 39, 521–533.

Medina, E.M., Fu, F., 2021. A new circular economy framework for construction projects. Proc. Inst. Civ. Eng.Eng. Sustain. 174 (6), 304–315.

Muñoz, S., Crawford, R.H., Hosseini, M.R., 2023a. The 9R Circularity Index and Closed-Loop Circularity Index Software Tools. https://doi.org/10.6084/m9.figshare.24155766.v1.

Muñoz, S., Hosseini, M.R., Crawford, R.H., 2023b. Exploring the environmental assessment of circular economy in the construction industry: a scoping review. Sustainable Production and Consumption. 42, 196–210.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60 (3), 498–508.

Niu, Y., Rasi, K., Hughes, M., Halme, M., Fink, G., 2021. Prolonging life cycles of construction materials and combating climate change by cascading: the case of reusing timber in Finland. Resour. Conserv. Recycl., p. 170.

Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216.

Peceño, B., Alonso-Fariñas, B., Vilches, L.F., Leiva, C., 2021. Study of seashell waste recycling in fireproofing material: technical, environmental, and economic assessment. Sci. Total Environ, p. 790.

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain. PBL Publishers.

Reich, R.H., Vermeyen, V., Alaerts, L., Van Acker, K., 2023. How to measure a circular economy: a holistic method compiling policy monitors. Resources, Conservation and Recycling 188, 106707.

Reike, D., Vermeulen, W.J.V., Witjes, S., 2022. Conceptualization of circular economy 3.0: synthesizing the 10R hierarchy of value retention options. In: Alvarez-Risco, A., Rosen, M.A., Del-Aguila-Arcentales, S. (Eds.), Towards a Circular Economy: Transdisciplinary Approach for Business. Springer International Publishing, Cham, pp. 47–69.

Rönnlund, I., Reuter, M., Horn, S., Aho, J., Aho, M., Päällysaho, M., Ylimäki, L., Pursula, T., 2016. Eco-efficiency indicator framework implemented in the metallurgical industry: part 1—a comprehensive view and benchmark. Int. J. Life Cycle Assess. 21 (10), 1473–1500.

Saaty, T.L., 1990. The analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559.

dos Santos Gonçalves, P.V., Campos, L.M.S., 2022. A systemic review for measuring circular economy with multi-criteria methods. Environ. Sci. Pollut. Res. 29, 31597–31611.

Schützenhofer, S., Kovacic, I., Rechberger, H., 2022. Assessment of sustainable use of material resources in the architecture, engineering and construction industry – a conceptual framework proposal for Austria. J. Sustain. Dev. Energy Water Environ. Syst. 10 (4).

Shooshtarian, S., Hosseini, M.R., Kocaturk, T., Arnel, T., Garofano, N., T., 2023. Circular economy in the Australian AEC industry: investigation of barriers and enablers. Building Research & Information 51 (1), 56–68.

Suárez-Eiroa, B., Fernández, E., Méndez-Martínez, G., Soto-Oñate, D., 2019. Operational principles of circular economy for sustainable development: linking theory and practice. J. Clean. Prod. 214, 952–961.

Taghikhah, F., Voinov, A., Shukla, N., 2019. Extending the supply chain to address sustainability. J. Clean. Prod. 229, 652–666.

Tazi, N., Idir, R., Ben Fraj, A., 2021. Towards achieving circularity in residential building materials: potential stock, locks and opportunities. J. Clean. Prod. 281.

UNEP, 2016. The Emissions Gap Report 2016: A UNEP Synthesis Report. United Nations Environment Programme.

UNEP, 2022. Global Status Report for Buildings and Construction.

Vegter, D., van Hillegersberg, J., Olthaar, M., 2023. Performance measurement system for circular supply chain management. Sustainable Production and Consumption 36, 171–183.

Vitale, P., Napolitano, R., Colella, F., Menna, C., Asprone, D., 2021. Cement-matrix composites using CFRP waste: a circular economy perspective using industrial symbiosis. Materials 14 (6), 1484.

WBCSD, 2023. Circular Transition Indicators V4.0. https://www.wbcsd.org/Programs/Circular-Economy/Metrics-Measurement/Resources/Circular-Transition-Indicators-v4.0-Metrics-for-business-by-business.

WBCSD, KPMG, Circular IQ, n.d. CTI Tool.

Wijewickrama, M.K.C.S., Rameezdeen, R., Chileshe, N., 2021. Information brokerage for circular economy in the construction industry: a systematic literature review. J. Clean. Prod. 313, 127938.

WorldGBC, 2019. Bringing Embodied Carbon Upfront.

Wouterszoon Jansen, B., van Stijn, A., Eberhardt, L.C.M., van Bortel, G., Gruis, V., 2022. The technical or biological loop? Economic and environmental performance of circular building components. Sustainable Production and Consumption 34, 476–489.

Zanni, S., Simion, I.M., Gavrilescu, M., Bonoli, A., 2018. Life cycle assessment applied to circular designed construction materials. Procedia CIRP 69, 154–159.

Zhai, J., 2020. BIM-Based Building Circularity Assessment from the Early Design Stages. Eindhoven University of Technology.

Zhang, N., Han, Q., de Vries, B., 2021. Building circularity assessment in the architecture, engineering, and construction industry: a new framework. Sustainability 13 (22).