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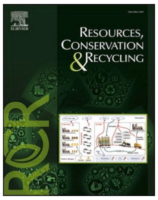

A novel circular economy framework: Assessing process circularity through resource flow and emissions analysis

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ABSTRACT

The urgent need for more sustainable resource management highlights the imperative for innovative approaches within the circular economy paradigm. The knowledge gap addressed is the complexity of circular economy assessments and the need for robust frameworks to accurately evaluate circularity within processes. This article introduces a new framework to assess process circularity aimed at minimising environmental impacts, mitigating climate change, and fostering sustainability. Built upon a systematic literature review done in prior research, it combines the strengths of existing models and addresses their knowledge gaps. Central to this framework is the Process Circularity Index (ProCI), customisable to accommodate diverse sectoral requirements. By considering key components like materials, energy, water, and waste storage, the framework provides a holistic perspective on process circularity, aligning with the goals of promoting cleaner manufacturing practices. Practical implementation and testing of the framework in real-world are highlighted as future research avenues to demonstrate effectiveness and applicability.

Notations

Indicators and indices	
ProCI	Process Circularity Index
CI	Circularity indicator or index
MCI	Material circularity indicator
ECI	Energy circularity indicator
WCI	Water circularity indicator
SCI	Storage circularity indicator
LFI	Linear flow index for materials
LFI_E	Linear flow index for energy
LFI_W	Linear flow index for water
SRI	Storage risk indicator
Weighted factors	
F_i	Weighted factor of the model component
F_{MCI}	Weighted factor of the material component in the assessment
F_{ECI}	Weighted factor of the energy component in the assessment
F_{WCI}	Weighted factor of the water component in the assessment
F_{SCI}	Weighted factor of the storage component in the assessment

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Indicators and indices		
Symbol	***Description***	***Unit***
Variables		
Materials		
V	Mass of virgin material used in the process	kg
W	Mass of waste	kg
M	Product mass	kg
W_F	Mass of waste generated by the recycling process that provides the materials used to manufacture a product	kg
W_C	Mass of waste generated by the recycling process after the useful life of the product	kg
F_R	Fraction of recycled materials	-
F_U	Fraction of reused products and/or components	-
F_P	Fraction of repaired materials	-
F_F	Fraction of refurbished materials	-
F_M	Fraction of remanufactured materials	-
F_{Pu}	Fraction of repurposed materials	-
C_U	Fraction of materials with a waste reuse scenario	-
C_P	Fraction of materials with a waste repair scenario	-
C_F	Fraction of materials with a waste refurbish scenario	-

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(*continued*)

Indicators and indices		
C_M	Fraction of materials with a waste remanufacture scenario	-
C_{Pu}	Fraction of materials with a waste repurpose scenario	-
C_C	Fraction of materials with a composting scenario	-
C_R	Fraction of materials with a waste recycling scenario	-
C_E	Fraction of materials with an energy recovery scenario	-
Energy		
E_{fossil}	Amount of fossil energy used in the process	kWh
E_{loss}	Amount of energy lost in the process	kWh
E_{total}	Total amount of energy used in the process	kWh
E	Amount of energy used for a process	kWh
E_{clean}	Fraction of clean energy used	-
$E_{recovered}$	Fraction of energy reused on site	-
η	Efficiency of the system	-
Water		
W_{virgin}	Volume of virgin water consumed	L
C	Volume of water consumed	L
W_{wasted}	Volume of untreated water generated	L
F_{Ru}	Fraction of water reused within a single process or use harvested water for another purpose, without treatment	-
F_{re}	Fraction of water recycled within the same or different process after treatment	-
F_{rain}	Fraction of rainwater used in a process	-
L	Fraction of total volume of water lost	-
C_{ru}	Fraction of water collected for reuse within a single process or use harvested water for another purpose, without treatment	-
C_{re}	Fraction of water collected for recycling on-site	-
Emissions		
GHG_{total}	The total greenhouse gas emissions	kg CO_2-e
EF_{ij}	Emission factor	kg CO_2-e/kWh
A_{ij}	Activity level associated with the gas and the energy source	-
GWP_i	Global Warming Potential of the gas over a specific time horizon	-

1. Introduction and background

In recent years, the imperative for sustainable resource management has become increasingly urgent despite escalating environmental challenges. Central to this endeavour is the concept of circular economy, which seeks to decouple economic growth from environmental degradation and resource depletion through the promotion of resource efficiency (e.g. recycling, reusing, repurposing, reducing) (Mukherjee et al., 2023; Shang et al., 2022). The concept of a circular economy (CE) can be described as the efficient utilisation of limited resources, increased application of renewable resources, the retrieval of materials at the conclusion of their lifecycle, and the restoration of natural systems (Mukherjee et al., 2023). As the global community strives to address pressing issues, such as climate change, biodiversity loss, and resource scarcity, the adoption of circular economy principles has emerged as a key strategy for achieving long-term sustainability goals (Kurnia et al., 2023).

While a circular economy offers promising solutions, its implementation requires robust frameworks for assessing the circularity of systems at different scales (e.g. organisations, processes, products, materials). Conventional approaches to evaluating resource management often cannot capture the multidimensional nature of circularity, hindering effective decision-making and resource allocation (Alivojvodic and Kokalj, 2024). For instance, one of the leading methodologies in the realm of circular economy, the material circularity indicator (MCI) developed by the Ellen MacArthur Foundation (2019), focuses on the analysis of materials and waste associated with a product, with the organisation's scope being determined as a synthesis of the product range within the organisation. This methodology is constrained to examine solely the origins of materials for a product and the subsequent management of waste generated during its production. Its applicability is limited by its narrow scope and necessitates modification to accommodate diverse end-of-life scenarios as per the 9R Framework. Valls-Val et al. (2022) analysed tools to measure the circularity of an organisation, emphasising clear differences in the results that are not comparable. Also, they indicated some tools are too time-consuming for the users and overall difficult to use.

The material flow methodology has been adapted for application across diverse industrial sectors and scopes. For instance, Madaster (2018) tailored this approach to the construction sector, focusing on materials and products utilised in building construction. However, the efficacy of this adaptation hinges upon the accuracy and reliability of the data input into the Madaster Platform, necessitating continuous development and updates. In addition, Khadim et al. (2022) summarised 35 circularity indicators for buildings. This is relevant because their work highlights the importance of adopting a holistic approach that considers various aspects of building design, construction, and end-of-life processes to enhance overall circularity.

Circularity assessment is a critical aspect of evaluating the effectiveness of circular economy strategies across various system levels. Guzzo et al. (2022) defined distinct levels of circular economy systems through their literature review. At the macro-level, circularity assessment encompasses broader societal and environmental impacts, including resource flows, policy frameworks, and overall sustainability outcomes. At the meso-level, assessments expand to consider entire sectors or industries, evaluating circularity in supply chains, production methods, and resource management practices. At the micro-level, assessments often zoom in on individual products or processes, examining factors such as material composition, resource efficiency, and waste generation. Despite focusing on the micro-level, research findings vary significantly, contributing to a noticeable gap in circularity assessments and their underlying principles. While Ahmad et al. (2024) emphasise the lack of economic metrics in micro-level analyses, Matos et al. (2023) present a summary of micro circularity indicators predominantly focused on economic and environmental dimensions. These discrepancies are prevalent in circular economy-related literature, highlighting the gap in the circularity assessments and their foundations. Moreover, Kowalski et al. (2023) emphasised the lack of universally accepted metrics for evaluating circular economy performance at the micro level, which poses a challenge for industrial enterprises aiming to adopt circular economy practices. Their study, focusing on the production system, included multiple processes of sodium tripolyphosphate production.

Product-level analysis remains a popular focus of circularity-related studies, allowing for hands-on analysis and feasible with readily available data from manufacturers. Jerome et al. (2022) reviewed 36 indicators at a product level, revealing numerous knowledge gaps, particularly within resource-based indicators. The authors discussed 4 indicators related to production losses, primarily in terms of material use, waste and energy intensity. They also stressed the importance of detailed assessment to include additional flows not accounted for due to assessment scope limitations. Recent research has studied the application of circular economy concepts and frameworks at a company level (Baumer-Cardoso et al., 2023; Heras-Saizarbitoria et al., 2023; Sacco et al., 2021).

Some studies combine different levels, such as de Souza et al. (2024), who adopted material flow analysis for countries, regions, and cities, thus integrating macro and *meso* levels. They also considered micro-level, evaluating multiple processes without distinct assessments for each process separately. While promising, this approach faces challenges with data availability, making it difficult for users to adopt.

Milanović et al. (2023) discussed process assessment as part of the product circularity assessments. They emphasised the importance of assessment of material circularity, but did not clarify how exactly process circularity should be measured. Di Maio et al. (2017) raised an issue of resource efficiency measurement and frameworks not being specific and robust. They proposed a value-based resource efficiency indicator that diverges from the traditional mass-based approach, making it adaptable for both process and product-level assessments. However, this method introduces challenges related to data availability and its applicability across stages of the supply chain.

Circular economy assessments have made strides at the product, organisation, and industry levels, a gap remains in tools that focus specifically on processes (Milanović et al., 2023). Most existing frameworks emphasise resource use and waste management for entire products or broader organisational activities. Moreover, processes are defined differently by different authors. For example, Liu (2024) focused on the transition process towards a circular economy, while Grimbert and Zabala-Iturriagagoitia (2024) concentrated on procurement processes for a circular economy. However, assessing circularity at the manufacturing process level is essential—it offers a closer look at how resources are used in day-to-day operations, helping to identify small changes that can make a big impact. This focus is especially valuable in industries where optimising individual processes can drive substantial improvements. However, due to the lack of targeted indicators and the complexities of collecting detailed data, process-level circularity remains underexplored.

2. State of the art in process circularity assessments

An initial search on Scopus using article titles for “circular economy” or “circularity” and “process” yielded 216 documents in English, with 100 of them being journal articles, half of which were published between 2023 and 2024. This search was further complemented with the following query: “circular*” and “process” and “indicator”. The temporal scope was also amended to include earlier articles with a high number of citations.

Many of the identified publications focused on specific processes while conducting circularity assessments. For instance, Kalemkerian et al. (2024) introduced a circular value stream mapping tool derived from a literature review and focus group discussion, which was tested in an agricultural case study to optimise operations while reducing environmental impacts. The key elements included material, energy, water, waste and by-products. Similarly, Sourabh et al. (2024) analysed the metal industry using a macroeconomic model to evaluate the circular economy process effectiveness of co-flowing primary and secondary metal production. While this model provides broader insights into production, conducting a more in-depth analysis would necessitate examining individual processes separately. Additionally, the model’s reliance on numerous assumptions and its lack of readily available data makes its practical application challenging.

Additionally, Nikolakis et al. (2024) proposed an eco-efficiency calculation of a system to assess processes through life cycle assessment (LCA) and life cycle costing (LCC). Their methodology required an ideal scenario to identify the benefits and costs of transitioning to it. They define a system as a sum of multiple manufacturing processes, acknowledging concerns about data availability and accuracy, especially for small and medium-sized enterprises (SMEs). Eco-efficiency of a system is a sum of eco-efficiency of each individual process extended for comparison of alternative CE strategies for each of the processes or process groups. Furthermore, Lokesh et al. (2020) introduced a new set of process-specific indicators for inclusion in life cycle assessments, such as process material circularity, circular-process energy intensity, circular-process waste factor, product renewability, circular-process feedstock intensity and hazardous chemicals.

Patil et al. (2023a) identified limitations in existing circularity assessments and advocated for a standardised, comprehensive methodology to enable accurate measurement across various systemic levels. The authors noted that factors such as inconsistent data quality, spatial and temporal variations, and market dynamics can influence assessment outcomes. In a follow-up chapter, Patil et al. (2023b) proposed a methodology and a set of indicators specifically for assessing circularity at the business level, emphasising the importance of standardised tools for businesses to effectively measure and report circularity progress. Their proposed metrics included wastewater, emissions, solid waste, recycling, remanufacturing and end-of-life management as essential elements of circular waste management. Although they consider production processes and stress the need for eco-design, their primary focus is on business operations. The authors also emphasised that circularity assessment should begin with an evaluation of raw materials, water, and energy consumption in relation to waste management and footprint reduction efforts.

De Pascale et al. (2021) reviewed CE 61 indicators across micro, *meso*, and macro levels, categorising them by CE principles and sustainability dimensions. The authors identified a gap in consistent assessment methodologies, particularly at the micro level, and advocated for integrated indicators that combine multiple dimensions to support a standardised CE framework. Similarly, Harris et al. (2021) conducted a scoping review of circularity assessment methods across different system levels. While numerous circularity indicators and metrics exist to measure material flow or value recirculation, the authors highlighted a lack of a strong connection between these indicators and environmental performance. They argued that current tools insufficiently track the environmental impacts arising across various system levels.

Focusing specifically on micro-level indicators, Matos et al. (2023) provided a comparative analysis of business-oriented circularity indicators, discussing their effectiveness in assessing progress toward a circular economy. The paper noted the reliance of several indicators on external data, such as market or regulatory conditions, which limits their practicality. Additionally, the study highlighted that most indicators focus narrowly on single dimensions, lacking a standardised, multi-dimensional approach.

Lamba et al. (2024) conducted a bibliometric analysis of 596 articles on CE and sustainable development (SD), identifying a gap in aligning CE metrics with SD goals and the need for greater stakeholder involvement in developing CE indicators and frameworks. They stressed the necessity of incorporating metrics relevant to practitioners to improve the utility of CE assessments in practice.

In a sector-specific study, Anastasiades et al. (2023) examined the most commonly used CE metrics and introduced a circular construction indicator framework tailored to the construction sector. The authors highlighted resource consumption and waste generation as key CE strategies, adopting a 4R approach. They also noted the importance of determining appropriate weighting factors to integrate various indicators effectively. A report by Circular Australia (2022) reviewed a range of CE metrics, emphasising how metrics such as waste generation, recycling rates, and material recovery can help organisations design waste out of operations and enhance resource efficiency. The report incorporated a seven-R framework – redesign, reduce, reuse, repair, remanufacture, recycle, and recover. Many of the shortlisted metrics, such as eco-efficiency or industrial symbiosis, were quite limited because of the challenges in data collection.

A highly-cited paper by Saidani et al. (2019) presented a taxonomy of CE indicators, criticising that the current circularity indicators do not consistently account for all possible CE loops. The authors emphasised that adopting circular economy strategies globally requires new business models, advanced technologies, greater expertise, and redefined industrial processes and product innovations. They viewed process assessment as an evaluation of the pre-process design and post-process resource effectiveness. However, an explicit circular economy indicator for process-level evaluation was not identified.

Corona et al. (2019) further explored this need by summarising existing CE metrics, underscoring the importance of including emissions and renewable energy sources in circular assessments—though these elements are often omitted due to the challenges in accurately estimating them. Vinante et al. (2021) identified resource consumption, particularly materials, energy, and water, as central to the circular economy's value chain, alongside the management of waste in all forms (solid, liquid, and gaseous). Iacovidou et al. (2017) added to this understanding by recognising resource flows as essential to circularity while incorporating economic and social metrics that extend beyond the traditional focus on materials and waste. The authors emphasised the need for simplicity and transparency while also refining the set of metrics through relevance to stakeholder goals. However, due to data limitations, many of these indicators are challenging to implement in practice, and certain metrics may vary significantly depending on geographical and sectoral contexts.

The diversity of CE indicators available is extensive, as seen in Muñoz et al. (2023), who reported over 249 indicators for CE assessments, and in the comprehensive review by Garcia-Saravia Ortiz-de-Montellano and van der Meer (2022), who identified >400. These authors proposed a CE framework organising indicators across several layers and categories. However, despite the abundance of metrics, the authors cautioned that many indicators are overly broad and thus difficult to quantify. They stressed the importance of carefully establishing the functional unit (to define performance requirements) and system boundaries (to clarify evaluation scope) to create effective circular economy assessment tools. While their framework includes metrics for both design and process levels, only a small fraction of indicators directly addresses process-level assessment.

Having an extensive array of indicators does not inherently improve CE assessments; in fact, a highly complex framework can deter implementation by industry practitioners. To enhance practical applicability, sector-focused frameworks are essential.

To summarise, despite the growing importance of circular economy principles, current frameworks for assessing circularity are limited in scope, particularly at the process level. Many existing models focus on product-level circularity or macro-level systems but fail to capture the nuanced resource flows and environmental impacts of individual processes. This gap hinders effective decision-making and resource optimisation. To address this, the research introduces a compound framework for assessing process circularity, which includes the customisable Process Circularity Index (ProCI). The ProCI has been specifically developed to provide a detailed and adaptable assessment of process-level circularity, addressing the limitations of existing models by integrating resource flow and operational emissions into a single comprehensive index. The ProCI framework is more adaptable than current methodologies, making it a valuable tool for both researchers and practitioners. By supporting sustainability goals such as reducing waste, optimising resource use, and mitigating environmental impacts, the framework holds significant value for real-world applications across various industries, contributing to the broader circular economy research and advancing sustainable industrial practices.

The remainder of the article is structured as follows. Section 3 presents the process circularity framework, explains its scope and specific components. Section 4 applies the proposed framework to a theoretical case study to demonstrate its applicability and performance. Section 5 discusses the benefits and limitations of the proposed framework, outlines future research directions, and concludes the article.

3. Methods

3.1. A new framework for assessment of process circularity

To address the existing gap within the scholarly and grey literature, the proposed framework is specifically designed to focus on the process level. The circular economy metrics were selected based on the previous work - systematic literature review and industry interviews (Pilipenets et al., 2024). The proposed framework, which introduces the Process Circularity Index (ProCI), builds upon our earlier findings on circularity challenges in waste management, especially within construction and demolition (C&D) contexts (Pilipenets et al., 2024). Our prior study identified the necessity of tailored circularity indicators due to the significant contributions of C&D waste to environmental burdens and the industry-specific stockpiling issues often overlooked in general circularity models.

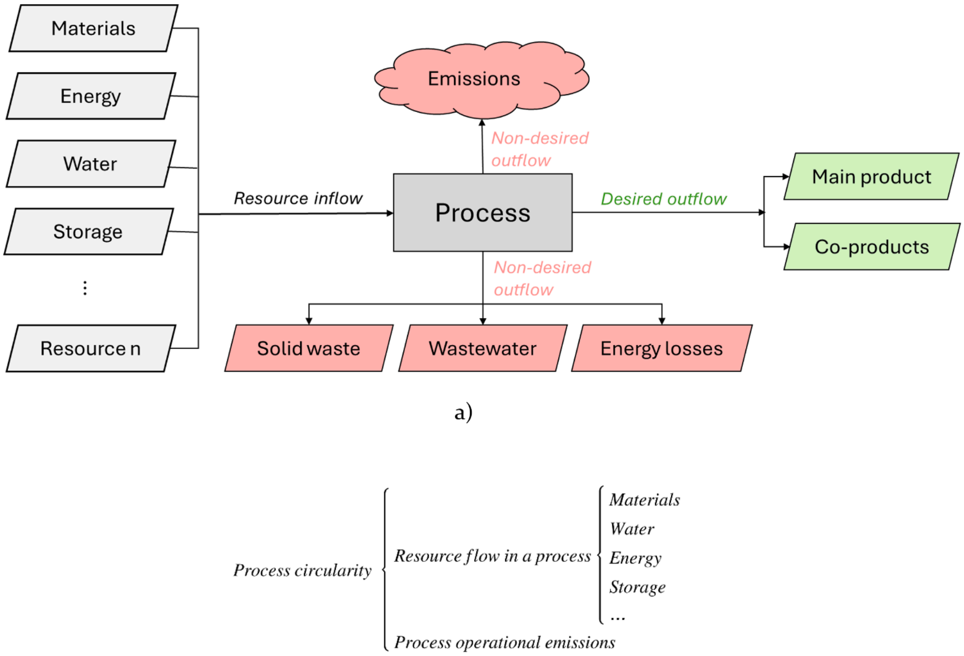
The ProCI is developed as an original index focusing on process-level assessment, distinct from any existing indices, including those highlighted in previous works. The new framework evaluates inflows and outflows specific to critical resources within processes, informed by our systematic literature review and insights gathered from industry practitioners through interviews (Pilipenets et al., 2024). Fig. 1, illustrating this resource flow, is an original contribution that operationalises our concept of inflow-outflow assessment, addressing identified needs for a clear process-level CE indicator. This model adopts a resource flow methodology (Platonov et al., 2020) to calculate the Process Circularity Index (ProCI). Based on the scope of the proposed model, the assessment focuses on some of the critical resources used in a process employing an inflow-outflow approach (Fig. 1).

There are various approaches to mapping resource flows, each drawing from distinct fields such as quality management, continuous improvement, environmental methodologies, and business process management (BPM). In quality management, resource flow assessments focus on minimising defects and optimising the use of materials to improve product quality and reduce waste (Defeo and Juran, 2010). Continuous improvement methodologies, such as Lean and Six Sigma, emphasise the flow of resources to eliminate inefficiencies and improve productivity within processes (Antony, 2006). Environmental methodologies, including life cycle assessment (LCA), track resource inputs and outputs to evaluate environmental impacts across a product or process lifecycle (Lavers Westin et al., 2019). Logical and BPM approaches often represent resource flows in terms of workflows or operational models, aiming to streamline processes and improve overall efficiency (van der Aalst, 2013). While each of these frameworks provide useful insights into resource flow, they often do not fully address the circularity needed for effective CE assessments. The Material Circularity Indicator from the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2019) is integrated into the proposed framework because of its precise focus on quantifying material retention and recovery throughout the lifecycle. MCI is widely adopted, and has been customised to fit specific industry needs in the past studies (Saidani et al., 2019).

Our proposed method involves tracking resources that enter (inflow) and exit (outflow) the system boundary (i.e. process) (Fig. 1). In the proposed framework, the term "resources" encompasses materials, energy, water, and other resources. The "inflow" refers to introducing these resources into the process. The "outflow" represents what happens to these resources after they have been utilised. For the outflow category, two main subcategories are used: desired outputs (the main product) and non-desired outputs (e.g. solid waste, wastewater, energy losses, emissions).

Greenhouse gas (GHG) emissions related to the process have substantial environmental implications, contributing to air pollution, climate change, ecosystem degradation, and other phenomena (Walker et al., 2018). GHG emissions can serve as an indicator of resource efficiency (Tang et al., 2023), with high emissions potentially signalling inefficient resource utilisation. Regulatory compliance is another important consideration, as many jurisdictions enforce limits on industrial process emissions (Olson, 2010). Factoring GHG emissions into the circularity assessment can help businesses ensure they adhere to these regulations. Furthermore, emissions reduction aligns with numerous United Nations' Sustainable Development Goals (United Nations, 2015). Therefore, including GHG emissions in the circularity assessment can contribute to the alignment of the process with broader sustainability objectives.

To analyse a process from different perspectives, the proposed model integrates two main components—resource flow and operational GHG emissions—along with their multiple subcomponents (Fig. 2) selected



a)

b)

Fig. 1. Scope of the proposed Process Circularity Framework (figure by the authors).

based on the previous studies (Pilipenets et al., 2024). Process circularity index and process operational GHG emissions are not isolated, but rather are a part of the system and must be considered together to fully understand the process. The proposed step-by-step approach to process circularity assessment is outlined in Fig. 3.

3.2. Introducing the process circularity index (ProCI)

The resource flow methodology is a widely used approach for monitoring and analysing the movement of resources within systems or industries (Platonov et al., 2020). By tracing the flow of resources from their sources to their destinations, this methodology offers a holistic view of resource utilisation patterns and helps identify inefficiencies or opportunities for improvement. However, one limitation of this methodology is its general focus on overall resource flows within systems or industries, rather than on specific processes or activities within those systems. This broader scope may sometimes make it challenging to pinpoint areas of inefficiency or to assess the circularity of individual processes accurately. The proposed Process Circularity Index (ProCI) aims to overcome these limitations by providing a more targeted assessment of circularity within specific processes, enabling more effective decision-making and resource optimisation efforts.

Eq. (1) defines ProCI, which encompasses various circularity subcomponents like material source sustainability, utilisation efficacy, waste minimisation, and reuse/recycling potential. Each subcomponent contributes to ProCI via specific criteria-based indices/indicators, integrated through weighted summation to derive ProCI, with weights based on their relative importance:

$$ProCI = \sum_{i=0}^{n} (iCI \cdot F_i) \tag{1}$$

where CI is a circularity indicator/index (between 0 and 1) for resource i, and F_i is a weighted factor of the model component (between 0 and 1). The calculation of the $ProCI$ yields a value ranging from 0 to 1. A value of 0 signifies a linear economy, indicating that the process is entirely linear, with no component of circularity. Conversely, a value of 1 denotes a fully circular process, implying that all resources are effectively utilised, waste is minimised, and materials are recycled or reused to the greatest extent possible. This equation possesses the flexibility to accommodate a different number of components within its structure and can be further expanded to include additional components when more data becomes available.

In our previous study (Pilipenets et al., 2024), insights from practitioners helped identify the most crucial metrics for circular economy (CE) assessments, including waste, materials, energy, greenhouse gas emissions, transport, labour, waste storage, and economic factors. Combining these insights with the literature review in Section 1, waste, materials, water, energy, and storage were selected as core metrics for assessing process circularity.

Labour, transport, and economic factors were not included in the current framework for several reasons. Labour metrics are generally associated with the social dimensions of sustainability rather than environmental or resource efficiency. Including labour metrics in circularity assessments would shift the emphasis from material and process efficiency to workforce management and employment practices, which, while valuable, do not directly contribute to reducing resource consumption, waste, or emissions. Labour considerations are also highly specific to business and industry types, making it challenging to standardise them within a general circularity metric framework. Tracking transport-related metrics demands extensive data on routing, fuel type, and distances travelled, which may not be feasible to include in a standardised process-focused CE framework where the emphasis is on material flows and energy use directly within the production cycle. Economic metrics such as profitability and cost savings are certainly critical for business viability but are often excluded in core CE frameworks focused on environmental metrics. While economic factors influence the adoption of CE practices, they are variable and subjective, influenced by market conditions, pricing, and policy incentives. Including economic considerations might dilute the focus on environmental impact and circularity goals, as these factors do not directly measure improvements in resource efficiency or waste reduction. Instead, they are often treated as secondary or supplementary to core CE metrics, which aim primarily to measure circularity performance based on physical and environmental outcomes. Thus, although not part of the current framework, labour, transport, and economic metrics should be

Fig. 2. Process circularity metrics (figure by the authors).

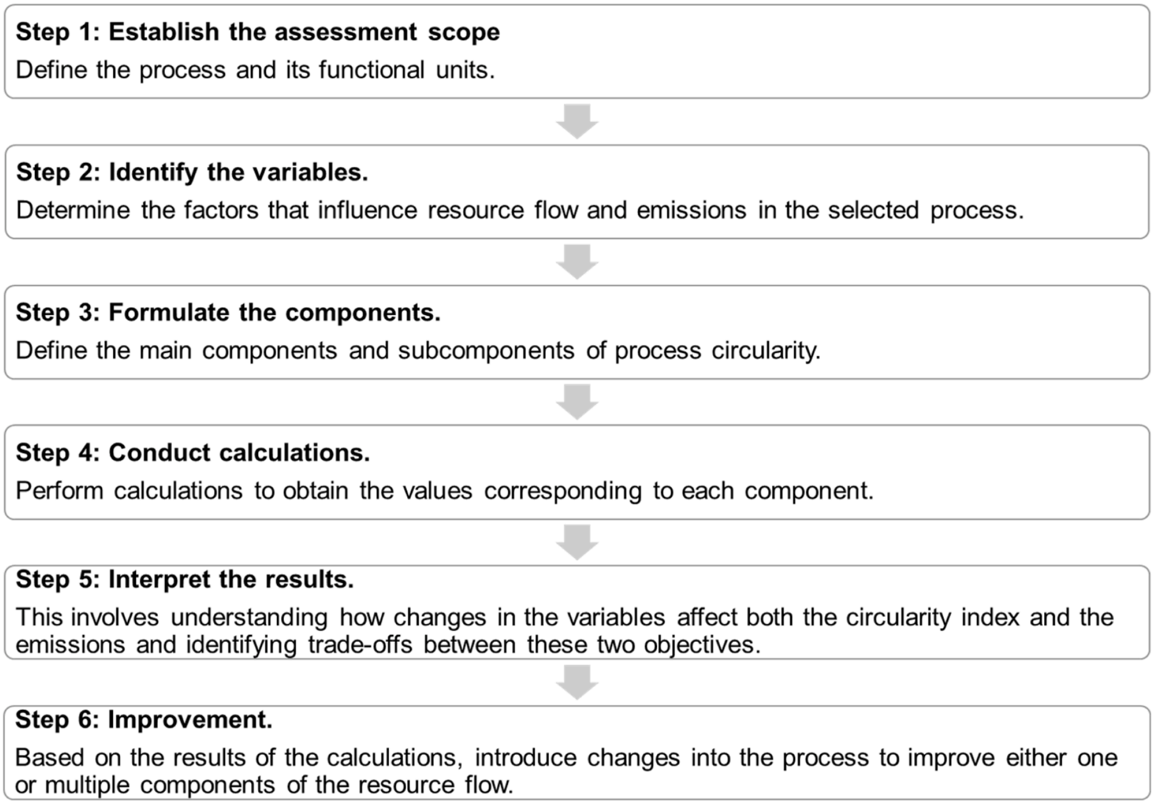
considered in future research when more data and more assessment methods are available.

$$ProCI = \sum_{i=0}^{4} (iCI \cdot F_i) = MCI \cdot F_{MCI} + WCI \cdot F_{WCI} + ECI \cdot F_{ECI} + SCI \cdot F_{SCI} \qquad (2)$$

where MCI is material circularity indicator, WCI – water circularity index, ECI – energy circularity index, SCI – storage circularity index; F_{MCI}, F_{WCI}, F_{ECI}, F_{SCI} are weighted factors for material, water, energy, and storage components in the assessment.

The weighted factor F_i plays a crucial role in the calculation, offering flexibility of the calculation and applicability of the model across various processes. It is used to assign varying degrees of significance to the components within the model and to give more or less influence to certain values. The weighted factor can also be utilised to exclude certain model components from the equation if they are deemed irrelevant to the specific type of process under assessment. In this case, the value of F_i can be assigned as a 0 (zero) if the component is not applicable to the process. For example, if a process does not involve energy to operate the machinery, the weighting factor can be taken as $F_{ECI} = 0$ to balance the weightings in the equation and focus on those components that are relevant to the process. Therefore, the energy component will be omitted from the equation. Similarly, when a particular component of the model lacks sufficient data, it can be temporarily excluded from the equation until adequate data is obtained.

Assigning an equal weighting factor (for example, 0.25 for a four-component assessment) is a baseline approach. However, other multi-criteria evaluation methods could also be considered to reflect the unique characteristics of each process more accurately. Multi-criteria decision techniques, such as Analytic Hierarchy Process (AHP) (Ho, 2008) or the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Sindhu et al., 2017), can provide ways to assign weightings based on specific goals or expert inputs. For example, Shaikh et al. (2024) used AHP to enhance decision-making for circular economy



Step 1: Establish the assessment scope

Define the process and its functional units.

Step 2: Identify the variables.

Determine the factors that influence resource flow and emissions in the selected process.

Step 3: Formulate the components.

Define the main components and subcomponents of process circularity.

Step 4: Conduct calculations.

Perform calculations to obtain the values corresponding to each component.

Step 5: Interpret the results.

This involves understanding how changes in the variables affect both the circularity index and the emissions and identifying trade-offs between these two objectives.

Step 6: Improvement.

Based on the results of the calculations, introduce changes into the process to improve either one or multiple components of the resource flow.

Fig. 3. A six-step approach to assessing process circularity.

and sustainability metrics in manufacturing. Additionally, García-Zamora et al. (2023) adopted fuzzy thresholds and minimum cost consensus to facilitate evaluation of CE indicators. Krstić et al. (2023) proposed a combination of axial-distance-based aggregated measurement and the best-worst method for the evaluation of the CE business models in agri-food sector. There is no unanimous way of evaluating the CE metrics, frameworks, and models. Further research is necessary to identify what weighting factors are the most appropriate for various processes.

3.3. Components of the process circularity index

The following sub-sections provide an in-depth explanation of the calculation of each component and subcomponents within the framework.

3.3.1. Materials

This model adopts the material flow analysis through a Material Circularity Indicator (MCI) proposed by Ellen MacArthur Foundation (2019) to facilitate a thorough examination of material flows. This methodological approach has shown widespread application in both industrial settings and academia (Gallo et al., 2023; Sekti and Singgih, 2022; Tashkeel et al., 2021). Therefore, the following formula of MCI is adopted:

$$MCI = 1 - LFI \tag{3}$$

where *MCI* is material a circularity indicator, *LFI* is a linear flow index.

This equation represents an adaptation of the formula by the Ellen MacArthur Foundation (2019) as it excludes F(X) but integrates additional items relevant to the process-level analysis. In the original *MCI by* Ellen MacArthur Foundation (2019), F(X) represents the utility factor of a product, integrating elements such as product lifespan, frequency, and intensity of use. This factor is useful in assessing product-level circularity, as it provides a measure of how effectively a product serves its purpose over time, thereby influencing its overall material circularity. However, at the process level, assessing circularity requires a more direct focus on material flow and resource efficiency specific to the process itself, rather than on the utility or lifecycle attributes of the end product. Process circularity evaluation prioritises inputs, outputs, and immediate resource interactions within the process boundaries, rather than attributes tied to product longevity or use intensity, which are typically addressed in product-level analysis. For instance, in a manufacturing process where the primary concern is raw material usage and waste minimisation, the product's lifespan or usage intensity has minimal relevance to the circularity of the process itself. Therefore, for process-level circularity, including F(X) could introduce unnecessary complexity without providing additional insights specific to resource flows within the process.

The LFI formula has been adopted from the Ellen MacArthur Foundation (2019) and modified to suit the process scope:

$$LFI = \frac{V + W}{2M} \tag{4}$$

where V is a mass of virgin material used in the process, W – mass of waste, M – product mass.

The first item in the linear flow index formula, virgin material, is proposed as follows:

$$V = M(1 - F_U - F_P - F_F - F_M - F_{Pu} - F_R) \tag{5}$$

where M is a product mass, F_U, F_P, F_F, F_M, F_{Pu}, F_R are the fraction of reused, repaired, refurbished, remanufactured, repurposed, recycled materials.

The main limitation of the Ellen MacArthur Foundation (2019) formula is that it focuses on Reuse and Recycling scenarios only. However, incorporating other Rs from the 9R framework (Potting et al., 2017) is crucial in assessing process circularity, as it provides a comprehensive view of resource usage and waste generation. Each R represents a different strategy for resource optimisation, thus offering a multi-faceted approach to sustainability. Therefore, complementary components have been incorporated into the equation to account for scenarios involving repair, refurbishment, re-manufacturing, and repurposing. Energy recovery was not included as part of material flow virgin material calculations to avoid clashing with the energy component of process circularity.

In calculating the amount of virgin feedstock, the term F_U denotes the fraction of materials derived from sustained production. The acquisition of data for this component presents a considerable challenge due to the inherent ambiguity in defining what constitutes "sustainable" production. Madaster (2018) have proposed to redefine F_U as the fraction of rapidly renewable materials. However, this modification might lead to an overlap with other items within the equation. Therefore, it is proposed that F_U be redefined to encompass the fraction of reused products and/or components, expressed as a percentage of the product mass.

The second component in the linear flow index formula, unrecoverable waste (Ellen MacArthur Foundation, 2019), necessitates an update to maintain consistency with the process scope and the 9R framework. Consequently, scenarios involving repair, refurbishment, re-manufacturing, and repurposing are integrated into the equation:

$$W = M(1 - C_U - C_P - C_F - C_M - C_{Pu} - C_C - C_R - C_E) \tag{6}$$

where M is the mass of waste, C_U, C_P, C_F, C_{Pu}, C_C, C_R, C_E are the fraction of materials with a waste reuse, repair, refurbish, re-manufacture, repurpose, composting, recycling, energy recovery scenario. Composting and energy recovery were added to the equation to encourage more strategies that help in decreasing the amount of waste going into landfill.

3.3.2. Water

Water usage has become a key focus in circular economy evaluations, with numerous studies exploring how water flows can be integrated into these assessments (Arora et al., 2022; Nika et al., 2020). Sartal et al. (2020) introduced a Water Circularity Index, which aligns with the methodology of material flow calculations as per the Ellen MacArthur Foundation (2019). A similar approach has been demonstrated by Kakwani and Kalbar (2022) who provided a more in-depth methodology for calculating a Water Circularity Indicator (WCI).

It is suggested to adopt the WCI proposed Kakwani and Kalbar (2022) with modifications to render it suitable for the process scope:

$$WCI = 1 - LFI_W \tag{7}$$

where LFI_W is a linear flow indicator for water:

$$LFI_W = \frac{W_{virgin} + W_{wasted}}{2W_{total}} \tag{8}$$

where W_{virgin} is the volume of virgin water consumed, W_{wasted} – volume of wastewater generated, W_{total} – the total volume of water used in a process.

Therefore, the WCI can be summarised as follows:

$$WCI = 1 - \frac{W_{virgin} + W_{wasted}}{2W_{total}} \tag{9}$$

Based on the different potential scenarios of the origin of water, to calculate the amount of virgin water used for a process, we differentiate between fresh water, water reused directly onsite, recycled water, and collected rainwater. This approach builds on Kakwani and Kalbar (2022) by integrating the potential scenario where collected rainwater is used within the process. Thus, the following equation can calculate the volume of virgin water used in a process:

$$W_{virgin} = C(1 - F_{Ru} - F_{\mathrm{Re}} - F_{rain}) \tag{10}$$

where C is the volume of water consumed, F_{Ru} is a fraction of water reused within the same process, without treatment (EPA Victoria, 2021), F_{Re} – fraction of water recycled within the same process after treatment (EPA Victoria, 2021), F_{rain} – fraction of rainwater used. The key distinction between reused and recycled water lies in whether the water undergoes a treatment process before it is reintegrated into the system. Other potential R-strategies are no included in the equation as they would not be applicable to the water circularity estimations.

In power plants, water is commonly used to cool down machinery, thus preventing overheating. After absorbing heat, this water is often cooled down in a cooling tower and reused in the same cooling process. This creates a closed loop that significantly reduces the amount of fresh water needed for the plant's operation. In the textile manufacturing industry, recycled water is extensively used. This sector requires substantial amounts of water for processes like dyeing and washing them post-treatment. Here, wastewater is treated to remove contaminants such as dyes, then recycled back into the manufacturing process for tasks like fabric washing.

Differentiating reused and recycled flows could allow the framework users to further customise the assessment by applying different weights to recognise that recycled (treated) water typically incurs additional energy and resource costs associated with the treatment process, while reused (untreated) water flows may have fewer associated impacts. Assigning different weights to reused and recycled water would enable a more accurate reflection of the trade-offs between resource efficiency and environmental costs in water management. For instance, a higher weight for reused water could incentivise direct reuse strategies that reduce both resource consumption and environmental impact. Conversely, giving recycled water a slightly lower weight would account for the additional resources involved in treatment, providing a more comprehensive picture of water circularity. This can help support more targeted decisions in process design, promoting sustainable water practices.

A great example of sustainable practice is using collected rainwater to clean metal parts. This is done through rainwater harvesting systems, which collect and store rainwater for use instead of treated water. This method has been effectively executed in the past, resulting in a significant reduction in the organisation's expenditure on water while simultaneously diminishing the necessity for treated water (CleanaWater, 2015).

When calculating the volume of wastewater generated (W_{wasted}), we consider scenarios when the water is reused for different manufacturing processes (i.e. other than the original process under study), either within the same facility or within other systems. We also consider the case when the used water is sent for recycling off-site (WBCSD, 2021):

$$W_{wasted} = C(1 - L - C_{Ru} - C_{\mathrm{Re}}) \tag{11}$$

where L is a fraction of total volume of water lost, C_{Ru} – fraction of water collected for reuse in a different system (i.e. used for purposes other than its original use), without treatment (EPA Victoria, 2021), and C_{Re} – fraction of water collected and sent off-site for recycling.

3.3.3. Energy

Energy is the second critical component of process circularity assessment. Numerous studies have incorporated energy flows into their circularity evaluations (Bowman et al., 2022; Burg et al., 2023; Zapelloni et al., 2019). Gonzalez Junca et al. (2021) discussed calculation of energy circularity indicators. However, their application is highly specialised and, as such, is not suitable for a broad process circularity assessment. To ensure the inclusion of energy flows in the assessment, a modified Energy Circularity Indicator (ECI) is proposed, designed to align with the material flow formula of the Ellen MacArthur :

$$ECI = 1 - LFI_E \tag{12}$$

where LFI_E is the linear flow index for energy.

Consistent with the calculations presented earlier, LFI_E can be expressed as follows:

$$LFI_E = \frac{E_{fossil} + E_{loss}}{2E_{total}} \quad (13)$$

where E_{fossil} is the amount of fossil energy used in the process, E_{loss} – the amount of energy lost in the process, E_{total} – the total amount of energy used in the process.

Therefore, the ECI can be summarised as:

$$ECI = 1 - \frac{E_{fossil} + E_{loss}}{2E_{total}} \quad (14)$$

Analogous to the material and water flow calculations, the focus of the energy flow calculation is to minimise the linear flow of energy. This means using less non-renewable energy, reducing energy losses, and increasing efficiency. The diverse sources of energy include oil, gas, renewable energy, among others (DCCEEW, 2023c). The assessment starts with the fossil energy as the first component in the linear flow equation. Fossil energy here refers to the fuels emitting substantial amounts of emissions (Shojaeenia et al., 2022). To calculate the fossil energy, the fraction of clean energy used for the process is used as it plays a crucial role in reducing environmental impact and promoting long-term viability of production processes. The adoption of clean energy is aligned with the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2015) as it encourages efficient use of resources and seeks to separate economic development from environmental harm. By giving precedence to clean energy, we are progressing towards sustainable consumption and production habits, which is the primary aim of SDG 12 (United Nations, 2015). Clean energy forms such as solar, wind, and hydropower emit far fewer greenhouse gases, the main cause of climate change. Hence, the use of renewable energy signifies our efforts to mitigate climate change and its effects.

The amount of fossil energy utilised for a process is proposed to be calculated using the following formula:

$$E_{fossil} = E_{total}(1 - E_{clean}) \quad (15)$$

where E is the amount of energy used for a process, E_{clean} – fraction of clean energy used.

The energy consumption (E_{total}) includes both primary and secondary energy, measured in kWh. This allows adding up energy consumption from different sources. Regarding primary energy used for the process, the potential clean energy flows (E_{clean}) only include the renewable energy generated on-site or nearby for product and parts manufacturing. These would include, therefore, solar thermal energy, biomass and biofuels energy, waste to energy (W2E) processes, on-site solar photovoltaics (PV), wind power or even a thermal energy from district heating and cooling systems (DH/DHC) if it comes from renewable sources or waste heat. The fraction of clean energy for electricity consumption (i.e. secondary energy) is defined by the share of clean energy technologies used to produce electricity in the region (e.g. country, state, city) (Hadley and Short, 2001). Taking Australia as an example, clean energy fraction for electricity can be estimated based on the share of renewable energy at a country level (30 %) or state level (100 % Tasmania, 40 % for Victoria) (DCCEEW, 2023a).

The amount of energy loss can be calculated as follows:

$$E_{loss} = E_{inflow} - (E_{total}\,\eta) - E_{\mathrm{recovered}} \quad (16)$$

where E_{inflow} refers to the total amount of energy that is supplied to a system or process for it to function, $E_{recovered}$ is a fraction of energy reused on site, η is the efficiency of the system.

This formula also accommodates a scenario when the energy used for a process can be captured and reused. For instance, in a steel manufacturing plant, high temperatures are required to melt the raw materials. This process generates a substantial amount of waste heat. A heat recovery system can capture this waste heat and use it to preheat the raw materials for the next batch, reducing the amount of energy required to reach the melting point (EPA USA, 2022). This not only makes the process more energy-efficient, but also reduces the overall carbon footprint of the manufacturing process.

3.3.4. Storage

Waste storage (storage) is included in the model to measure process circularity due to its significant impact on organisational efficiency and environmental regulations, as highlighted by Pilipenets et al. (2024). The Storage Circularity Indicator (SCI) aims to provide a comprehensive assessment of waste management practices, including space utilisation for this purpose, enhancing circular economy strategies and policies. Through a risk management approach, the indicator ensures consistency in evaluations.

Thirteen distinct risk categories are identified based on the guideline for stockpile management (EPA SA, 2020), with each assigned a severity score (from 1 to 5) based on its environmental and operational impacts. The key risks were summarised as follows: pollution of waters, leaching or runoff of contaminants and particulates; heat generation with potential to cause fire; generation of litter; dust emissions; biogas emissions; vermin; adverse visual amenity; stockpile instability; inadequate platform stability and suitability; excessive accumulation of material; abandonment of stockpiles and avoidance of regulatory regime; mischievous or criminal vandalism (EPA SA, 2020; Pilipenets et al., 2024). The risk likelihoods should be established by the user of the framework based on the thorough analysis of the waste storage associated with the process under assessment. Further discussion of the risks, their severities, and likelihoods can be found in (Pilipenets et al., 2024).

Following Pilipenets et al. (2024), the calculation of the SCI is as follows:

$$SCI = 1 - SRI \quad (17)$$

where SRI is a storage risk indicator that can be calculated as follows:

$$SRI = \frac{\sum_{i=0}^{n}(Riskseverity_i \cdot Risklikelihood_i)}{(Riskseverity_{\max} \cdot Risklikelihood_{\max})n} \quad (18)$$

Storage is crucial in circular processes due to its impact on material usability and quality (especially for hazardous materials like electronic waste), and legal obligations to manage associated risks. Efficient storage practices can minimise waste and maximise resource use. The storage circularity indicator, although formulated differently from other indices due to data availability and unique storage dimensions, addresses these concerns by providing a comprehensive assessment of storage-related risks.

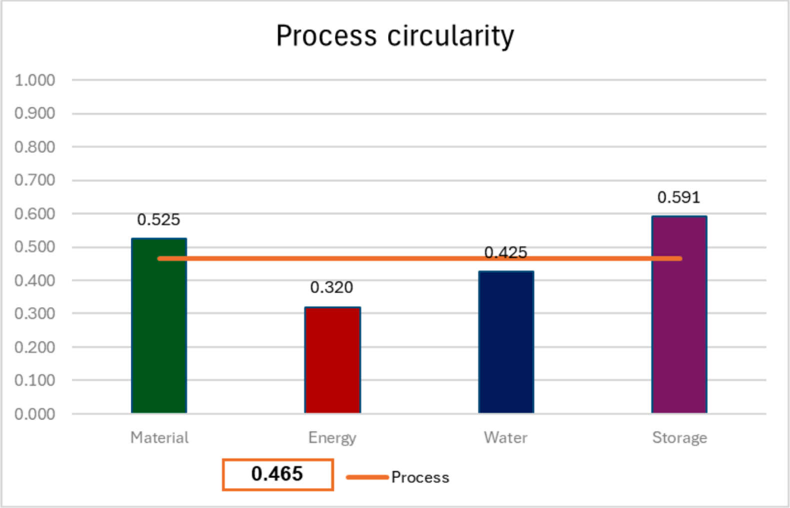
3.4. Process emissions

The calculation of the total GHG emissions involves a detailed process that accounts for the specific gas (for example, carbon dioxide, methane, nitrous oxide) and energy source (e.g. electricity, combustion of natural gas, etc.). This is done by multiplying the emission factor, which is specific to each GHG and energy source combination, by the magnitude of the activity associated with that combination.

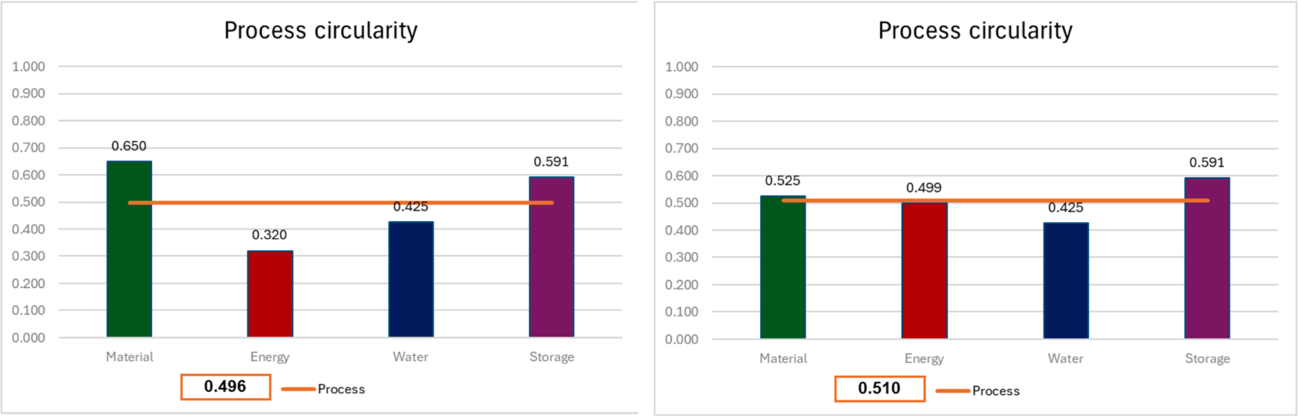
$$GHG_{total} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(EF_{ij}\,A_{ij}\right)\,GWP_i \quad (19)$$

where m is the number of different GHG gases considered, n is the number of different energy sources considered, EF_{ij} is the emission factor for the ith gas from the jth energy source. This factor represents the amount of GHG emissions per unit of activity for a specific combination of gas and energy source (e.g., kilograms of CO_2 per kilowatt-hour of electricity generated from coal), A_{ij} is the activity level associated with the ith gas and the jth energy source (e.g., the amount of electricity generated from coal), GWP_i is the Global Warming Potential of the ith gas over a specific time horizon typically 100 years (this measure allows the effect of different gases to be expressed in terms of CO_2 equivalents). The first summation sums the emissions across all gases considered and the second summation indicates that for each gas, the emissions are summed across all energy sources considered.

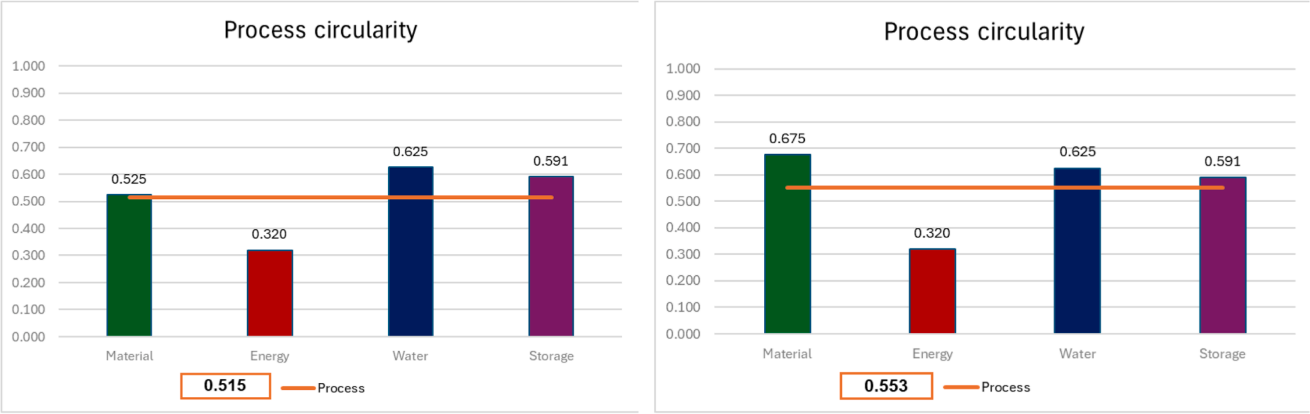
Emission factors serve as a critical tool in the quantification of greenhouse gas emissions, facilitating the conversion of a unit of activity into its corresponding emissions equivalent. Emission factors can be adopted at either a national or regional level, reflecting the geographical variability in emission sources and energy production methods. These factors are typically enumerated in greenhouse gas accounting calculations. For instance, the Australian Government published the Australian National Greenhouse Accounts Factors report, which provided detailed emission factors for Scope 1, Scope 2, and Scope 3 emissions (DCCEEW, 2023b). Scope 1 and Scope 2 emissions can be used depending on the energy consumption associated with a specific energy commodity within a process (Clean Energy Regulator, 2023). Scope 1 emissions encompass



a) Scenario 0



b) Scenario 1 c) Scenario 2



d) Scenario 3 e) Scenario 4

Fig. 4. Results of circularity assessment of a concrete block manufacturing process.

direct emissions from owned or controlled sources, while Scope 2 accounts for indirect emissions from the generation of purchased electricity, steam, heating, and cooling consumed by the reporting entity. It is important to note that an emission factor is intrinsically tied to a specific activity, and the nature of the activity determines the emission factor employed. This approach ensures that all relevant GHG emissions, be they direct or indirect, are accounted for in the assessment of a process's environmental impact.

4. Framework application through a theoretical case study

To illustrate the application of the proposed framework, a theoretical case study on concrete block manufacturing is presented. The assessment focuses on the manufacturing process of a standard concrete block (190 × 190 × 390 mm, mass of 14.9 kg) in Australia (Cement Concrete and Aggregates Australia, 2010, 2020; National Masonry, 2015). The key data and assumptions can be summarised as follows:

- Materials: 1.9 kg of cement, 5.0 kg of sand, 7.0 kg of gravel
- Water: 1.5 litres per standard concrete block
- Energy: 2 MJ for mixing, molding and curing
- Manufacturing location: Victoria, Australia
- Waste storage on site

To evaluate the circularity of the concrete block manufacturing process, five unique scenarios have been designed. Starting from a baseline process, each scenario introduces gradual changes to enhance process efficiency. These scenarios facilitate an examination of how specific operational improvements influence the circularity outcomes of the selected process.

- Scenario 0: Baseline scenario – standard manufacturing process.
- Scenario 1: Half of the materials used for manufacturing of a concrete block are recycled materials.
- Scenario 2: Using waste heat recovery systems to account for 20 % of the energy used in the process.
- Scenario 3: Reuse of processed water – 20 % on-site and 20 % off-site (Cement Concrete and Aggregates Australia, 2007).
- Scenario 4: 20 % of waste being reused. Additional 10 % of waste products converted into aggregate for new concrete (Cement Concrete and Aggregates Australia, 2014).

The baseline scenario (Fig. 4a) represents the standard concrete block manufacturing process in Victoria, Australia, with no additional circularity measures. As the baseline, it establishes the starting point of material, water, and energy usage without the incorporation of recycled materials, waste reuse, or energy and water recovery. This provides a benchmark for evaluating the impact of improvements in subsequent scenarios. The total process GHG Emissions were estimated to be 0.476 kg CO2-e, and the ProCI was evaluated at 0.465 (see the supplementary files for the detailed calculations).

By substituting half of the raw materials with recycled equivalents, Scenario 1 demonstrates a noticeable shift towards material circularity from 0.525 up to 0.65 (Fig. 4b). It reduces dependence on virgin materials, aligning with CE goals of resource conservation and waste reduction.

Scenario 2 integrates waste heat recovery systems that offset 20 % of the energy required for mixing, molding, and curing. The ProCI results show an improvement in energy circularity (from 0.32 to 0.499) due to decreased reliance on external energy sources (Fig. 4c).

Incorporating water reuse strategies, with 20 % reused on-site and another 20 % off-site, showcases water circularity improvements from 0.425 to 0.625 (Fig. 4d). Reduced water consumption leads to lower resource input, highlighting the role of water recovery in closed-loop systems and minimising water waste and dependency on external resources.

In the final scenario, 20 % of manufacturing waste is reused, and an additional 10 % is repurposed as aggregate for new concrete. This scenario illustrates an approach to minimise landfill dependency and enhance circularity in both material use and waste management. The material circularity score is higher (from 0.525 to 0.675), reflecting the integration of waste back into the manufacturing process and reducing the need for virgin aggregates.

The ProCI values across five scenarios indicate how specific changes contribute to circularity at the process level, going from the baseline value of 0.465 up to 0.553 in the final scenario. Scenarios 1 through 4 each illustrate the incremental gains achieved by targeting different aspects of the manufacturing process, from materials and energy to water and waste reuse. The results highlight that while each strategy individually contributes to circularity, the combination of these strategies within a single process framework yields the most comprehensive improvements.

5. Discussion and conclusions

The proposed framework advances research on circular economy by providing a step-by-step approach to assess process circularity. It allows the users to analyse and compare how processes perform regarding such items as emissions, material use, waste generation, water use, energy consumption and waste storage. This can allow them to identify which process components are performing best in terms of circularity, and which components require attention to become more circular in the future.

For example, if a manufacturing process has a low score within the energy component of the framework, more energy-efficient equipment could be installed to achieve an overall higher circularity rating. Adopting renewable energy sources, such as solar or wind, can reduce dependence on non-renewable resources. Installing energy recovery systems, like waste heat capture, can improve overall efficiency, and process optimisation can lower energy consumption.

Similarly, low material scores could encourage users to increase the fraction of reused or recycled materials in their manufacturing processes. Incorporating recycled or repurposed materials can reduce reliance on virgin resources. Designing for modularity and disassembly would allow materials to be reused or refurbished in a long-run, while optimising production processes can minimise scrap and off-cuts as a short-term solution.

If water circularity score is low, implementing closed-loop water systems to reuse water on-site can significantly reduce freshwater usage. Technologies for water treatment and recycling can further lower consumption, and rainwater harvesting systems can supplement water needs.

To improve the waste storage circularity score, improved storage practices can be used, such as dedicated areas for reusable or recyclable materials. Separating waste streams on-site can facilitate recycling or repurposing efforts, while smart waste-tracking systems can optimise waste management and minimise on-site storage needs.

The assessment of process circularity holds significant importance across various fields, particularly manufacturing. Evaluating process circularity can help identify inefficiencies, enabling the implementation of strategies to optimise resource utilisation, minimise waste, and enhance overall sustainability. This can contribute to the realisation of a circular economy within the manufacturing sector, promoting environmental stewardship while also potentially leading to cost savings and competitive advantages.

The assessment of process circularity is not confined to the manufacturing sector but extends to a multitude of other fields. For instance, within the construction industry, such assessment can serve as a critical tool in informing the design and execution of building projects, with a focus on enhancing material reuse, reducing waste, and promoting energy efficiency. Regarding the waste management sector, this assessment would play a pivotal role in the development and implementation of strategies aimed at waste reduction, recycling, and recovery. Similarly, in the energy sector, process circularity assessment can be beneficial in optimising energy production and consumption processes, promoting the use of renewable resources and minimising waste and greenhouse gas emissions. In the transportation sector, this assessment could guide the transition towards more sustainable modes of transport and logistics operations. Within the agriculture sector, such assessment could guide the implementation of sustainable farming practices, such as precision agriculture, that maximise resource efficiency and minimise environmental impact. Consequently, the applicability of process circularity assessments spans across various sectors, contributing significantly to the advancement of sustainable practices and facilitating the transitions towards a circular economy. The insights gained from such assessments can inform policymaking, guide research and development efforts, and shape industry best practices, driving progress towards more sustainable and circular industrial processes.

The framework presented in this article is conceptual. Therefore, the absence of empirical validation for the application of this framework is a limitation. Further research is necessary to test this framework in case studies with real-world data to verify its practical applicability for different processes and sectors of the industry. Future research should also investigate how additional components, such as social and economic factors, can be integrated into the framework.

The weighted factors for the proposed components were selected as equals for simplicity. An alternative approach is to use expert elicitation to obtain these values. This method involves gathering input from subject matter experts on the topic at hand, which can provide more nuanced and context-specific values for F_i. This might lead to more accurate and reliable results, especially in complex or specialised scenarios. Moreover, multi-criteria decision methods should be explored to identify specific weightings for various processes. However, it is important to note that the quality of the results heavily depends on the expertise and reliability of the elicited experts.

To conclude, this article introduces a new approach to assessing circularity within the scope of processes, filling a crucial gap in the existing literature. By adapting predominant methodologies to the process level, we offer a fresh perspective on circularity assessments, providing a valuable tool for researchers and practitioners. Our framework, particularly the Process Circularity Index, offers a customisable solution tailored to the specific needs and requirements of different sectors, fostering inclusivity and versatility. By considering key components such as materials, energy, water, and storage, our framework provides a holistic perspective on process circularity.

Importantly, we highlight the potential of this framework to contribute to proactive and collaborative efforts aimed at promoting resource equity and sustainable resource use. By analysing resource flows and process operational emissions, our framework facilitates a comprehensive evaluation of circularity, enabling informed decision-making and targeted interventions to minimise environmental impacts.

Future research should involve the practical implementation and testing of our framework in real-world contexts to validate its effectiveness and refine its application. By adopting the proposed framework, manufacturers can evaluate the circularity of their processes, identify any roadblocks and find solutions through sustainable resource management practices, advancing the manufacturing circular economy.

CRediT authorship contribution statement

Olga Pilipenets: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Tharaka Gunawardena:** Writing – review & editing, Validation, Supervision, Methodology. **Felix Kin Peng Hui:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Priyan Mendis:** Supervision, Funding acquisition. **Lu Aye:** Writing – review & editing, Visualization, Validation, Supervision, Resources.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.108083.

Data availability

Data will be made available on request.

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