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Building circularity performance model: a weighted multi-level assessment framework aligned with ISO standards

Saba Mani and Gayani Karunasena
School of Architecture and Built Environment, Deakin University, Geelong, Australia
M. Reza Hosseini
Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, Australia, and
Abid Hasan
School of Architecture and Built Environment, Deakin University, Geelong, Australia

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Abstract

Purpose – This paper proposes the building circularity performance (BCP) model to address fragmentation in existing building circularity assessments, which lack comprehensive coverage of circular economy (CE) aspects, standardized KPI weightings and multi-level evaluation across buildings.

Design/methodology/approach – Using a design science research approach, a holistic and weighted assessment framework spanning five building levels (material, subcomponent, component, system and building) was developed. The BCP integrates 52 validated and weighted key performance indicators (KPIs) covering material flows, waste, energy, water, CO_2 emissions and design strategies, aligned with ISO 20887 and ISO 59020. The model was demonstrated through a single case study, and evaluated through an expert focus group, four design scenarios and sensitivity analyses of KPIs and weights.

Findings – Results show that circularity performance improves most through strategies extending building lifespan, promoting modularity and optimizing renewable resource use. The findings reveal that circularity emerges from the interaction of material, environmental and design strategies rather than isolated interventions. Sensitivity analyses confirm that the model is both responsive and robust, with bounded variations in outputs and consistent scenario rankings under input and weight changes.

Originality/value – The novelty of BCP lies in its systematic integration and weighting of multiple KPIs in various CE dimensions through a five-level structure. BCP advances existing approaches by integrating previously overlooked dimensions, including locality, hazardous content, environmental performance and design strategies such as repairability and take-back systems, within a single building assessment framework. It also contributes to the Sustainable Development Goals by supporting climate-resilient, resource-efficient and circular building practices.

Keywords Circularity model, Building circularity indicators, Circularity evaluation, Circular built environment, Environmental assessment, Building circularity measurement

Paper type Research article

1. Introduction

The building sector, accounting for around 50% of global raw material use, 36% of energy consumption, and 39% of emissions (Norouzi *et al.*, 2021), plays a critical role in the shift from a linear to a Circular Economy (CE) (Kirchherr *et al.*, 2023; Zuo and Zhao, 2014; Swarnakar and Khalfan, 2024). In buildings, this requires a shift in design and construction practices, supported by robust tools to measure circularity performance (Khedmati-Morasae *et al.*, 2024;

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Muñoz *et al.*, 2024; Pradeep *et al.*, 2025). CE in buildings promotes resource optimization through reuse, flexibility, and adaptability, ensuring that materials and components are designed for disassembly, reuse, or recycling (WBCSD, 2022; Abad *et al.*, 2024). Despite increasing interest, practical application of CE principles in building design remains fragmented, partly due to the lack of measurable and standardized indicators (Gillott *et al.*, 2023; Ellen MacArthur and Granta, 2019). A robust circularity assessment requires integrating Key Performance Indicators (KPIs) to evaluate adherence to CE principles that capture material reuse, recycling, and bio-based inputs (Moraga *et al.*, 2019; Tokazhanov *et al.*, 2022). While KPIs and Life Cycle Assessment (LCA) provide valuable insights, they alone are insufficient for decision support. This highlights the need for integrated and standardized assessment approaches that can support decision-making at early design stages, where the potential for circularity improvements is highest (Khedmati-Morasae *et al.*, 2024; Muñoz *et al.*, 2024; Hosseini *et al.*, 2015). Therefore, a unified composite index is needed to synthesize multiple KPIs (dos Santos Gonçalves and Campos, 2022; Lovrenčić Butković *et al.*, 2023).

Existing building circularity assessment methods attempt to quantify circularity through KPIs and mathematical aggregation, yet they remain limited in scope and integration. Material flow-based metrics such as MCI (Material Circularity Indicator) and CTI (Circular Transition Indicator) primarily assess input–output flows, often overemphasizing recycling while neglecting environmental performance and design strategies, and may introduce biases toward heavier materials (Saidani *et al.*, 2019; Matos *et al.*, 2023; Jiang *et al.*, 2022a; Walker *et al.*, 2023). Although some studies have attempted to address these issues by incorporating economic value, design-for-disassembly criteria, or BIM-based tools (Jiang *et al.*, 2022a; Zhang *et al.*, 2021b; Cottafava and Ritzen, 2021), these approaches remain partial and inconsistent. More broadly, existing methods vary significantly in scope, structure, and assumptions, leading to fragmented and non-comparable results across studies (De Pascale *et al.*, 2021; dos Santos Gonçalves and Campos, 2022; Khadim *et al.*, 2022; Mani *et al.*, 2025). They often rely on incomplete indicator sets, with limited integration of key CE dimensions such as energy, water, emissions, and design strategies, and rarely capture the hierarchical nature of buildings or full lifecycle impacts (Moreno *et al.*, 2016; Saidani *et al.*, 2019; Matos *et al.*, 2023). In addition, the lack of systematic KPI weighting and alignment with CE principles, such as the 10R hierarchy, reduces their ability to prioritize strategies and may lead to overestimation of circularity performance (Muñoz *et al.*, 2024; Mani *et al.*, 2025; Muñoz *et al.*, 2024; Mani *et al.*, 2025,). Consequently, these limitations undermine the practical applicability of existing models, as stakeholders face challenges in interpreting results, comparing alternatives, and effectively using them as decision-support tools during the design stage.

Recent advances, such as digital material passports, circular building indicators, and platform-based assessment tools, have improved data availability and traceability of materials. However, these developments mainly focus on data management and transparency, rather than providing an integrated analytical framework that links material data with environmental performance and design strategies across building levels. As a result, a gap remains in translating these data-driven approaches into comprehensive decision-support tools for circular building design.

Overall, these issues point to a broader problem: current BC assessment approaches are fragmented, inconsistent, and insufficiently aligned with the complexity of building systems. They often fail to capture the interdependencies among materials, subcomponents, components, and systems (by ignoring design strategies), as well as the interaction among circularity, design strategies, and environmental performance. They also ignore the relative importance of various CE strategies. This gap highlights the need for a structured, multi-level, multi-dimensional, and weighted framework that can provide a holistic and reliable assessment of circularity in building design. Therefore, three key research gaps remain: (1) the lack of a comprehensive framework that integrates material, environmental, and design-related circularity dimensions; (2) the absence of structured multi-level assessment capturing interactions across all building levels; and (3) the limited use of systematic KPI weighting to support prioritized and decision-oriented evaluation. To address these gaps, this paper aims to develop, validate, and evaluate a comprehensive and decision-oriented framework for assessing building circularity performance at the design stage. In response, the paper proposes the Building Circularity Performance (BCP) model, a comprehensive, structured, and weighted assessment model for evaluating BC. The novelty of BCP lies in its integration of systematically validated KPIs across material inflows and outflows, energy renewability, water circularity, CO_2 emissions, and design strategies, integrated with a weighting through expert input. This paper has three objectives: (1) develop a structured BCP framework incorporating weighted KPIs; (2) validate the applicability of the BCP model; and (3) evaluate and refine the model.

Section 2 reviews BC assessment frameworks and highlights research gaps. Section 3 outlines methodology. Section 4 presents BCP and its formulas. Section 5 provides results and discussions. Finally, Section 6 concludes with contributions and future directions.

2. Background

Over the past decade, numerous BC assessment models have been proposed to quantify the integration of CE strategies across design, construction, operation, and End-of-Life (EOL) (Zhai, 2020). To understand how circularity is assessed, it is first necessary to conceptualize how CE principles are translated into measurable indicators. The theoretical foundation of this research is grounded in CE theory, which conceptualizes circularity as a systemic approach to maintaining the value of materials, components, and resources throughout the lifecycle by replacing linear "EOL" thinking with regenerative and closed-loop systems (WBCSD, 2022). This perspective is operationalized through core CE principles of regenerate, narrow, slow, and close resource loops, which guide decision-making toward minimizing resource consumption, extending product lifespans, and reintegrating materials into productive cycles (Çetin *et al.*, 2021; Bocken *et al.*, 2016). These principles are further translated into actionable strategies through the 10R hierarchy, which prioritizes higher-value interventions such as refuse, rethink, and reduce over lower-value recovery processes like recycling and energy recovery (Reike *et al.*, 2022; Moraga *et al.*, 2019). At the building level, these strategies are implemented through circular design practices, including adaptability, disassembly, durability, and resource efficiency, which enable the practical integration of CE within design processes (WBCSD, 2022). Consequently, KPIs in this study are derived as measurable representations of these interconnected CE principles, strategies, and practices, allowing the conceptualization of circularity to be translated into a structured and quantifiable assessment framework. However, the field remains fragmented, with inconsistent terminologies and uneven coverage of indicators. To address these challenges, this section provides a critical overview of 36 methods across six analytical categories (Table 1).

The evolution of these methods reflects a fragmented landscape, where models differ significantly in their conceptual foundations, scope, and methodological assumptions. As demonstrated in Table 1, various metrics vary in what they measure, how they define circularity, and which lifecycle stages and strategies they prioritize. These variations lead to inconsistent interpretations of circularity performance across studies.

Level of applicability. BC metrics vary significantly in their level of application, from material-level metrics such as MCI (Ellen MacArthur and Granta, 2019) and CTI (WBCSD, 2023), to single-indicator approaches such as Flex (Geraedts, 2016) for adaptability, MRPI for material recovery (Bechthold and Mayer, 2017), and R-EOL for EOL reuse potential (Akanbi *et al.*, 2019a), to building-level integrated metrics such as BCI (Verberne, 2016), its variations like PBCI (Cottafava and Ritzen, 2021) and WBCI (Khadim *et al.*, 2023), and other composite indexes like BCES (Medina and Fu, 2021). However, this diversity in applicability levels introduces a fundamental limitation: most metrics fail to capture the hierarchical and

Table 1. Critical review of existing building circularity methods

	Level of applicability			Lifecycle stage				CE cycles	
Metric	Material	Single	Building	Extraction/ Manufacturing	Construction	Operation	End-of-life	Technical	Biological
1. MCI	✓			✓		✓	✓	✓	✓
2. CTI	✓			✓		✓	✓	✓	
3. Flex 4.0		✓		✓	✓	✓	✓	✓	
4. MRPI		✓		✓	✓	✓	✓	✓	✓
5. R-EOL		✓					✓	✓	
6. 3DR		✓		✓	✓	✓	✓	✓	
7. EURECA		✓		✓	✓	✓	✓	✓	
8. KAD		✓		✓	✓	✓	✓	✓	
9. BCI-Verberne			✓	✓	✓	✓	✓	✓	
10. BCI-Vliet			✓	✓	✓	✓	✓	✓	
11. BCIX			✓	✓	✓	✓	✓	✓	
12. CI			✓	✓	✓	✓	✓	✓	
13. BWPE			✓	✓	✓	✓	✓	✓	
14. RAT			✓	✓	✓	✓	✓	✓	
15. D-DAS			✓	✓	✓	✓	✓	✓	
16. PCB			✓	✓	✓	✓	✓	✓	
17. BCAS			✓	✓	✓	✓	✓	✓	
18. CBA			✓	✓	✓	✓	✓	✓	
19. BCI and PBCI			✓	✓	✓	✓	✓	✓	
20. BCRC			✓	✓	✓	✓	✓	✓	✓
21. BC			✓	✓	✓	✓	✓	✓	
22. BCES			✓	✓	✓	✓	✓	✓	✓
23. CCEF			✓	✓	✓	✓	✓	✓	
24. MCI’			✓	✓	✓	✓	✓		
25. CirBIM			✓	✓	✓	✓	✓	✓	
26. CE index			✓	✓	✓	✓	✓	✓	
27. CCS			✓	✓	✓		✓		
28. CC			✓	✓	✓	✓	✓	✓	

(*continued*)

Table 1. Continued

	Level of applicability			Lifecycle stage				CE cycles	
Metric	Material	Single	Building	Extraction/ Manufacturing	Construction	Operation	End-of-life	Technical	Biological
29. CCI			✓	✓	✓	✓	✓	✓	
30. WBCI			✓	✓	✓	✓	✓	✓	✓
31. CBT			✓	✓	✓	✓	✓	✓	
32. One Click LCA			✓	✓	✓	✓	✓	✓	
33. M-CEF			✓	✓	✓	✓	✓	✓	✓
34. WBCI + LCA			✓	✓	✓	✓	✓	✓	✓
35. TMD			✓	✓	✓	✓	✓	✓	✓
36. CARES			✓	✓	✓	✓	✓	✓	✓

	KPIs classification						KPIs weights		10R strategies					
Metric	Material	Waste	Design	Energy	Water	CO_2 emissions	Yes	No	Refuse	Rethink	Reduce	Reuse/ . . . /Repurpose	Recycle	Recover
1. MCI	✓	✓						✓			✓	✓	✓	✓
2. CTI	✓	✓		✓	✓	✓		✓			✓	✓		✓
3. Flex 4.0			✓					✓		✓				
4. MRPI	✓	✓	✓			✓		✓				✓	✓	
5. R-EOL	✓							✓						
6. 3DR	✓	✓	✓					✓				✓		
7. EURECA	✓	✓	✓					✓		✓		✓	✓	
8. KAD			✓					✓		✓				
9. BCI-Verberne	✓	✓	✓					✓			✓	✓	✓	✓
10. BCI-Vliet	✓	✓	✓					✓			✓	✓	✓	✓
11. BCIX	✓	✓	✓					✓			✓	✓	✓	✓
12. CI	✓	✓	✓					✓			✓	✓	✓	✓
13. BWPE	✓	✓	✓					✓				✓	✓	
14. RAT	✓	✓	✓					✓				✓	✓	

(*continued*)

Table 1. Continued

	KPIs classification						KPIs weights		10R strategies					
Metric	Material	Waste	Design	Energy	Water	CO_2 emissions	Yes	No	Refuse	Rethink	Reduce	Reuse/ . . . /Repurpose	Recycle	Recover
15. D-DAS	✓	✓	✓					✓				✓		
16. PCB	✓	✓	✓	✓	✓			✓			✓	✓		✓
17. BCAS	✓	✓	✓					✓			✓	✓	✓	✓
18. CBA						✓		✓					✓	
19. BCI and PBCI	✓	✓	✓	✓		✓		✓			✓	✓	✓	
20. BCRC	✓	✓		✓	✓			✓			✓	✓	✓	
21. BC	✓	✓	✓					✓			✓	✓	✓	
22. BCES	✓	✓		✓		✓		✓			✓	✓	✓	
23. CCEF			✓					✓				✓		
24. MCI’	✓	✓	✓					✓			✓	✓	✓	✓
25. CirBIM	✓	✓		✓		✓		✓			✓	✓	✓	
26. CE index	✓	✓		✓		✓		✓			✓	✓	✓	✓
27. CCS	✓	✓	✓	✓	✓			✓			✓	✓	✓	
28. CC			✓					✓		✓		✓		
29. CCI	✓	✓	✓					✓			✓	✓	✓	
30. WBCI	✓	✓	✓					✓		✓	✓	✓	✓	✓
31. CBT			✓					✓	✓			✓		
32. One Click LCA	✓	✓	✓				✓			✓	✓	✓	✓	✓
33. M-CEF	✓	✓	✓				✓				✓	✓	✓	
34. WBCI + LCA	✓	✓	✓			✓		✓		✓	✓	✓	✓	✓
35. TMD	✓	✓	✓	✓			✓		✓		✓	✓	✓	
36. CARES	✓	✓	✓					✓			✓	✓	✓	✓

Note(s): [1] Ellen MacArthur and Granta (2019), [2] WBCSD (2023), [3] Geraedts (2016), [4] Bechthold and Mayer (2017), [5] Akanbi *et al.* (2019a), [6] O’Grady *et al.* (2021), [7] Van Gulck *et al.* (2021), [8] Ollár *et al.* (2022), [9] Verberne (2016), [10] Van Vliet (2018), [11] Alba Concept (2018), [12] Madaster (2018), [13] Akanbi *et al.* (2018), [14] Akanbi *et al.* (2019a), [15] Akanbi *et al.* (2019b), [16] PlatformCb’ (2020), [17] Zhai (2020), [18] BAMB (2020), [19] Cottafava and Ritzen (2021), [20] González *et al.* (2021), [21] Zhang *et al.* (2021a), [22] Medina and Fu (2021), [23] Dams *et al.* (2021), [24] Jiang *et al.* (2022a, b), [25] Göswein *et al.* (2022), [26] Lei *et al.* (2022), [27] Fagone *et al.* (2023), [28] Gillott *et al.* (2023), [29] Anastasiades *et al.* (2023), [30] Khadim *et al.* (2023), [31] Arup and Ellen MacArthur (2022), [32] One Click LCA (2023), [33] Amarasinghe *et al.* (2024), [34] Khadim *et al.* (2025), [35] Lau *et al.* (2025), [36] Vásquez-Cabrera *et al.* (2025)

Source(s): Authors’ own work

interdependent nature of buildings. Material-level metrics often overestimate circularity due to assumptions of ideal reuse and limited attention to inter-component relationships, particularly in complex building systems (Conte and Brogna, 2019; Verberne, 2016). Single-indicator methods offer valuable insights into specific KPIs or aspects (e.g. adaptability or recovery potential), but lack broad system integration and typically underrepresent design strategies critical for circularity (Mani *et al.*, 2025). This limits their usefulness for holistic decision-making.

In contrast, building-level metrics aim to offer a more comprehensive assessment of circularity by addressing the entire building system. Examples include BCI (Verberne, 2016), its variations like PBCI (Cottafava and Ritzen, 2021) and WBCI (Khadim *et al.*, 2023), and other composite indexes like the BCES (Medina and Fu, 2021). Some of these metrics are modified adaptations of the MCI, including MCI′, which uses economic value instead of mass to avoid bias toward heavy materials (Jiang *et al.*, 2022b), and CI by Madaster (2018). Some metrics have been developed for specific contexts, like TMD by Lau *et al.* (2025) for Hong Kong buildings. This innovative framework, not derived from previous methods, includes indicators across three dimensions of technology, material, and design, which are relevant to Hong Kong's context and urban challenges. However, even these building-level models often fail to fully capture the hierarchical structure and dynamic lifespan of buildings. They often disregard the connections between all levels or layers of a building. This limitation overlooks how circularity performance propagates through all building levels, resulting in overestimating the circularity value (Conte and Brogna, 2019). Consideration of circularity assessment at all building levels is essential for creating buildings that are adaptable, efficient to disassemble, and aligned with circular practices, including re-use and recycling (ISO, 20887, 2020). Also, design-oriented KPIs like adaptability and disassembly need to consider the unique lifespans of each layer (Coenen *et al.*, 2021).

Life cycle stage coverage. An effective circularity assessment should address all life cycle stages, according to life cycle thinking perspective (Khadim *et al.*, 2023). Some existing metrics focus on early (extraction/manufacturing) and late (EOL) life cycle stages while overlooking mid-life stages such as transportation, on-site construction, and operation, despite their substantial impacts (Colarossi *et al.*, 2022; ISO 14044, 2006; Khadim *et al.*, 2023). As illustrated in Table 1, metrics like CCS assess only construction (Fagone *et al.*, 2023), while MCI and CTI address manufacturing stages (Mani *et al.*, 2025). This partial lifecycle consideration limits the ability of these models to capture the full resource implications of buildings, as all stages can significantly influence environmental performance and resource flows (Nässén *et al.*, 2007).

Focus on CE cycles. CE includes two cycles: the biological (returning biodegradable materials to nature) and the technical (restoring products and materials through reuse, repair, and recycling) (Kirchherr *et al.*, 2023; Ellen MacArthur and Granta, 2019). Many metrics consider only the technical cycle, limiting their applicability to bio-based materials (Table 1). A holistic CE assessment should encompass both cycles, recognizing the significance of both cycles. This limits the application of metrics to bio-based materials, especially as regenerative materials become increasingly important in circular and sustainable construction (Mouton *et al.*, 2023; Ellen MacArthur and Granta, 2019).

KPIs classification inclusion. KPIs form the foundation of circularity assessment models, yet their selection and application vary widely across studies. From a theoretical perspective, KPIs represent the operationalization of CE principles and strategies (Reike *et al.*, 2022; Moraga *et al.*, 2019). Many KPIs have been developed to capture specific CE practices. Additionally, ISO 20887 (2020) and ISO 59020 (2023) standards classify KPIs into six main areas: material, waste, energy, water, CO_2 emissions, and design. However, prior studies show that most of these indicators remain concentrated on recycling and EOL management, with limited attention to higher-value strategies such as reuse, repair, and resource efficiency (Kristensen and Mosgaard, 2020; Khadim *et al.*, 2022). Most existing metrics focus heavily on material and waste KPIs (Table 1) like recycled content and waste minimization (Khadim *et al.*, 2022; Zhang *et al.*, 2021a), while overlooking energy, water, emissions, and design-related KPIs such as modularity and adaptability, despite their importance in minimizing waste and life-time extension (Coenen *et al.*, 2021; Kristensen and Mosgaard, 2020; Saidani *et al.*, 2019). Biological-cycle KPIs are rarely addressed, limiting comprehensive evaluation. This reflects a broader misalignment between CE theory and its measurement, where higher-order strategies are underrepresented despite their greater impact on reducing resource consumption.

KPIs weights considerations. A critical limitation of existing BC assessment methods is the limited consideration of KPI weighting, where most frameworks implicitly assume equal importance across KPIs. This assumption contradicts CE theory, which emphasizes that strategies differ in their effectiveness and value contribution, as reflected in the 10R hierarchy (Reike *et al.*, 2022). In practice, higher-order strategies such as refuse, rethink, and reduce have significantly greater potential to minimize resource consumption compared to lower-order strategies such as recycling or recovery (Khaw-ngern *et al.*, 2021). One Click LCA incorporates differentiated weighting across material sources and EOL scenarios, assigning higher weights to reuse, recycling, and renewable content, and lower weights to downcycling, incineration, and landfilling, but still does not reflect the 10R hierarchy (Kirchherr *et al.*, 2017) and treats renewable, reused, and recycled materials equally. This highlights a broader gap in current models, where weighting factors often overlook the strategic priorities embedded in CE principles (Mani *et al.*, 2025). This limitation potentially overestimates circularity performance by assigning equal importance to fundamentally different actions.

10 R strategies. Circularity in buildings is often reduced to material recirculation. However, CE theory conceptualizes circularity more broadly as a regenerative system based on principles such as narrowing, slowing, closing, and regenerating resource flows (Konietzko *et al.*, 2020). These principles are operationalized through strategies such as the 10R framework, which prioritizes higher-order interventions (e.g. refuse, rethink) over lower-value recovery processes (Reike *et al.*, 2022). Despite this theoretical foundation, most existing metrics emphasize lower-priority CE strategies (reuse, reduce, and recycle) while neglecting higher-priority strategies like rethink and refuse (Mani *et al.*, 2025; Khadim *et al.*, 2022; Zhang *et al.*, 2021b). These high-level strategies have the greatest potential to minimize resource use (Hosseini *et al.*, 2023). In practice, strategies such as refusing unnecessary new construction (refuse strategy), can minimize resource consumption (Arup and Ellen MacArthur, 2022). Recycling, while common, ranks lower due to degradation and high energy inputs (Yang *et al.*, 2023), while strategies like remanufacturing, enhance circularity by preserving product value (Mesa *et al.*, 2018). This misalignment with CE theory limits their ability to capture the true circular potential of buildings. Comprehensive consideration of 10R strategies is essential for informed circular design decisions (Zhang *et al.*, 2021a).

In summary, existing methods often focus narrowly on material flow or EOL performance, overlook mid-life phases, omit biological cycle considerations, misalign KPIs and lack weighting systems, and underrepresent CO_2, design, energy, and water and high-priority 10R strategies. These gaps highlight the need for a holistic, design-informed BC assessment model that integrates both CE cycles, aligns with ISO standards, covers all lifecycle stages and key CE aspects, and prioritizes CE strategies. To address these gaps, this study aimed to develop an integrated assessment model (BCP) to provide a standardized method for evaluating building circularity at the design stage. To ensure robustness, the model's design considered key quality requirements (Corona *et al.*, 2019; Kulakovskaya *et al.*, 2023): validity (accurately measuring CE progress), reliability (producing consistent results across users and contexts), and utility (ensuring practicality, transparency, and ease of use). Finally, the model tailored to the needs of diverse stakeholders—architects, consultants, policymakers, and developers—seeking a transparent, decision-oriented framework for improving circularity in buildings. The next section outlines the Design Science Research (DSR) methodology adopted to achieve these objectives.

3. Methodology and research design

This study employed DSR to develop and validate a practical assessment model for BC. DSR emphasizes iterative cycles of problem identification, artifact creation, and evaluation (Peffers *et al.*, 2007), making it particularly suited to bridging theoretical knowledge gaps and practical needs in construction management (Elghaish *et al.*, 2023; Többen and Opdenakker, 2022). DSR includes six stages: problem identification, objective definition, design and development, demonstration, evaluation, and communication (Peffers *et al.*, 2007). The first two stages were used to identify research gaps and define objectives (Section 2). The next sections focus on the subsequent stages: design, development, demonstration, and evaluation of the BCP model. Figure 1 depicts how DSR guided this research.

3.1 Design and development

Following recommendations in the literature that circularity metrics should be built on existing frameworks and standards, rather than creating entirely new methods (Jiang *et al.*, 2022a), BCP was developed by extending MCI and WBCI. While MCI is a widely recognized metric and WBCI adapts it for buildings, both have limitations. This study addresses their limitations by proposing a novel and comprehensive framework, aligned with the research gaps identified in Section 2 and ISO 20887 (2020) and ISO 59020 (2023) standards. The former standard defines design strategies across five hierarchical levels: material, subcomponent, component or assembly, element, and system. To reduce complexity, the component and element levels were merged, forming a five-level structure. ISO 59020 (2023) standard guided the measurement stages: (1) boundary definition; (2) circularity calculation and data collection; and (3) circularity evaluation and reporting. At each level, circularity is calculated by aggregating relevant KPIs weighted through FAHP analysis. The process begins at the material level (MC), followed by the subcomponent (SCC), component (CC), system (SC), and building (BCP) levels.

Once the framework was structured, KPIs were first identified through a meta-synthesis of micro-level circularity indicators. The literature search was conducted across major academic and gray databases using predefined keywords related to CE and building circularity indicators. Studies were screened based on relevance to circularity assessment and inclusion of quantitative indicators, while specific-focused or qualitative studies were excluded. The identified KPIs were then validated and weighted through two Fuzzy Delphi Method (FDM) rounds with 17 experts. Delphi studies typically involve relatively small expert panels, especially when participants are homogeneous (Lilja *et al.*, 2011). A sample size of approximately 10–15 experts is often sufficient to achieve reliable consensus (Skulmoski *et al.*, 2007). Prior studies in circularity and sustainability assessment in construction have used panels ranging from 7 to 39 participants (Chen *et al.*, 2018; Hendiani and Bagherpour, 2019; Kumar and Anbanandam, 2019; Ocampo *et al.*, 2018; Tokazhanov *et al.*, 2022; Van Vliet, 2018; Vijayakumar *et al.*, 2023). Participants were purposively selected based on their expertise in CE, sustainability, and the construction industry, including academics and industry professionals. The expert panel represented diverse professional roles and geographic contexts

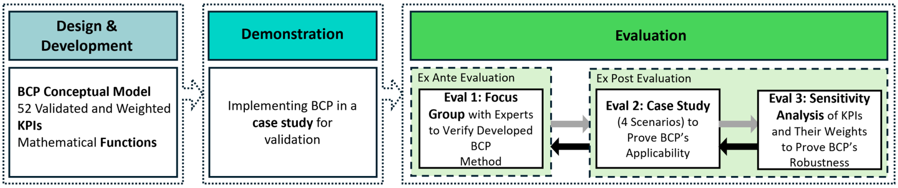

Figure 1. BCP development based on design science research methodology. Source: Adopted from Peffers *et al.* (2007))

to ensure a broad perspective. The FDM process was used to achieve consensus on the relevance and applicability of KPIs to the building context. Detailed information on the literature search strategy, inclusion/exclusion criteria, KPI selection process, expert recruitment, and the FDM procedure is provided in Mani *et al.* (2026b). The validated set includes 52 KPIs covering material flows, energy renewability, water circularity, CO_2 emissions, and design strategies was later weighted using FAHP. Detailed formulas are provided in Section 4.

As no established benchmark exists for ideal circularity, BCP expresses performance as a percentage alignment with CE principles. This study introduces a scoring system inspired by sustainability certification frameworks such as LEED and BREEAM (BRE Global, 2021; U. S. Green Building Council, 2024) and prior circularity frameworks by Bovea and Pérez-Belis (2018) and Geraedts (2016). Circularity performance ranges from 0 to 100%, with levels categorized as depicted in Table 2.

3.2 Demonstration

To demonstrate the practical implementation of BCP and learn from real-world applications, this study used the case study method (Peffers *et al.*, 2007). Case studies are widely used in construction research to reflect real-life complexity (Lucko and Rojas, 2010; Eftekhari *et al.*, 2022; Ahmadi Eftekhari *et al.*, 2022), and enables an in-depth understanding of processes and challenges to drive improvements (Ponelis, 2015; Mani *et al.*, 2022). The model was applied in a defined, realistic scenario case study that represented typical buildings. This approach has been applied in several circularity studies (Dams *et al.*, 2021; Khadim *et al.*, 2025; Shin and Kim, 2024; Mani *et al.*, 2026a). The subsequent sections describe the case study application process.

3.2.1 Case study definition and modeling. A typical single detached house in Australia with a 50-year lifespan was selected (Table 3). This scenario was deliberately defined based on the verified KPIs, ensuring that each KPI could be meaningfully evaluated within a realistic yet representative building context. It also drew upon the scenarios proposed by Dams *et al.* (2021) and aligned with relevant CE policies and standards, including ISO 59020 (2023), ISO 20887 (2020), and the NSW Government (2023) circular design guidelines.

The case represents a circular building characterized by adaptive reuse and modular design, reflecting key CE principles such as longevity, flexibility, and material reuse. Retrofitting an existing structure and using a previously occupied site enabled assessment of *refuse unnecessary new construction* and *site quality* KPIs. Materials were defined as bio-based, reused, remanufactured, and recycled to capture both CE cycles and material-related KPIs. Similarly, design-related KPIs like *modularity*, *prefabrication*, *disassembly*, *repairability*, *transportability*, and *take-back systems* were also embedded to ensure full compatibility with BCP requirements.

Table 2. The classification of circularity level and scores in this study

Circularity level	% score	Description
Very low	<30 (0.30)	Urgent alignment of the redesign with circular design guidelines is required
Low	≥30 (0.30)	Redesigning the product to align with circular design guidelines is considered compulsory
Moderate	≥45 (0.45)	Incorporation of circular design guidelines is recommended
Good	≥70 (0.70)	No significant improvement is necessary in the product design
Excellent	≥85 (0.85)	No specific action is required to improve circularity

Source(s): Authors' own work

Table 3. Case study scenario – definitions regarding CE KPIs

Key CE parameters	Case study scenario
Construction method	Retrofitting/Reusing of an existing building structure
Materials sources	Remanufactured/Bio-based materials (such as reclaimed natural timber for framing, studs, and joints, and sheep's wool batts for insulation)
CE design practices consideration	Modular building system- prefabricated three-dimensional modules (e.g. wall panels, roof trusses) manufactured offsite and assembled onsite Using dry, mechanical connections for easy disassembly of components A comprehensive take-back system is in place for all components
Construction waste destination	Materials are reused/recycled/remanufactured
Site condition	Built on a previously occupied site

Source(s): Authors' own work

Then, the building geometry was created using Carbon Designer 3D, a tool provided by One Click LCA. This feature generates basic building structures for different geographical regions, requiring minimal user input, and delivers reasonable estimates regarding the scale and quantity of materials. Detailed information is presented in Table A1 in Appendix. The building's size and complexity were deliberately chosen to ensure the analyses remained manageable.

3.2.2 Data collection and inputs. Bill of Materials was obtained through the Carbon Designer 3D tool, consisting of 11 elements, along with various materials. The required data, including input/output materials, average lifespan, hazardous waste, total GWP, and energy consumption, were gathered from drawing documents, Environmental Product Declarations (EPDs), One click LCA database, EC3 (Embodied Carbon in Construction Calculator) tool, manufacturers' reports, and relevant literature (Krausmann *et al.*, 2017; Vieira *et al.*, 2017; Vieira and Huijbregts, 2019). While the BCP model relies on these secondary data sources, it is acknowledged that these inputs may introduce variability and uncertainty. EPD data can vary depending on system boundaries, assumptions, and manufacturer-specific processes, while regional differences in material production, energy mix, and supply chains may influence environmental performance indicators. In addition, certain parameters, such as recycling efficiency and end-of-life scenarios, are subject to assumptions due to limited data availability. To address these limitations, this study utilized standardized and widely recognized data sources and applied consistent assumptions across all scenarios. Additionally, EPDs are standardized and International Reference Life Cycle Data (ILCD)-recognized data sources that support consistent and robust life cycle assessments, and they are increasingly adopted across the construction industry (Moré *et al.*, 2022; Soust-Verdaguer *et al.*, 2022; Waldman *et al.*, 2020). To support the assessment process, data analysis was conducted within Excel datasheets.

3.3 Evaluation

Evaluation is a critical component of DSR, ensuring that the developed artefact is both theoretically sound and practically useful (Peffers *et al.*, 2012). In DSR, evaluation can focus either on the design characteristics of the artifact before it is built (ex ante) or on how the completed artifact performs in use (ex post) (Sonnenberg and Vom Brocke, 2012). In this study, three distinct evaluation activities (Eval 1 to Eval 3) were carried out to assess both the design structure and utility of BCP (Figure 1).

3.3.1 Eval 1: focus group (ex ante). Following initial model development, a focus group session was conducted to evaluate and refine the BCP's clarity, completeness, and practical utility. Focus groups are widely used in DSR to obtain reflective, consensus-based insights, and model refinement (Hevner and Chatterjee, 2010; Rabiee, 2004). Four experts with backgrounds in sustainable construction, circular design and assessment, waste management, and environmental assessment participated (Table 4). The group size falls within the optimal range of 4–6 participants (Hevner and Chatterjee, 2010; Morgan, 1997), which allows for different opinions while maintaining a manageable and interactive discussion. This size is suitable for DSR, as the artifact can be complex, and engaging larger groups may hinder clear and effective interactions compared to simpler topics like a marketing campaign (Hevner and Chatterjee, 2010). Participants were purposively selected for their expertise in CE implementation in the built environment. All participants had over seven years of relevant experience, ensuring a balance of academic and industry perspectives (Table 4).

The session, conducted online in April 2025, lasted about one hour and followed an exploratory format focused on refining the model rather than testing its efficiency. Discussions were structured around three evaluation dimensions drawn from objectives defined in Section 2: *Validity* assessed whether the model measures what it intends to measure, *reliability* focused on whether it produces consistent, robust results, and *utility* considered its practicality and usability. Nine semi-structured questions guided the discussion. Recordings were transcribed and thematically analyzed using template analysis to identify recurring suggestions, which informed subsequent refinements to the BCP.

3.3.2 Eval 2: scenario-based assessment (ex post). To evaluate the applicability and responsiveness of BCP, four building design scenarios were developed, ranging from linear to highly circular configurations. Three additional scenarios were defined based on the base case (Section 3.2), which represents the most circular scenario. Scenario-based evaluation is widely used in circularity assessment to test model behavior under varying conditions (Dams *et al.*, 2021; Khadim *et al.*, 2025). In this study, it enabled assessment of the model's ability to differentiate levels of circularity and to capture the impact of design and material decisions on

Table 4. Profile of the experts for focus group

ID	Group	Occupation	Experience	Description[a]
P1	Industry/ Academic	University lecturer and researcher	13 years	Member of many Australian and Victorian waste management associations and scientific committee member for international scientific institutions, developing policy recommendations for a range of public sector and industry associations
P2	Academic	University lecturer and researcher	13 years	Active researcher in CE, leading several research projects related to CE and carbon reduction in construction projects, leader and member of various international and Australian research-based institutions
P3	Industry	Circular economy specialist and consultant	8 years	Advising many projects in the built environment, contributed to the development of a national guidance on building disassembly, providing CE related governance models, policy briefings, and strategic plans for international and national initiatives
P4	Industry	Researcher and CE consultant	7 years	Active researcher in CE and net zero carbon, contributed to the sustainability and CE assessment of several projects in the built environment

Note(s) [a]The descriptions are slightly modified to maintain the anonymity of experts

Source(s): Authors' own work

performance. By comparing circularity scores across scenarios, the evaluation tested whether the model responds consistently to increasing implementation of CE principles.

The assessment relied on the refined set of KPIs and equations, including those updated after focus group feedback, and used the same data sources, methodological approach, and principles outlined in Section 3.2. Detailed descriptions of the scenarios are provided below, with the variations in their specifications listed in Table 5. Similar to the BCP demonstration (Section 3.2), Carbon Designer 3D was used to model the scenarios, and LCA was utilized to assess environmental impacts.

Scenario 1 reflects a conventional construction approach on a new site using primarily virgin materials, with no consideration of modularity, disassembly, or circular design strategies. Scenario 2 introduces a prefabricated steel-framed system with partial use of recycled materials and improved resource efficiency, although circular design considerations remain limited. Scenario 3 further advances circularity by incorporating bio-based and recycled materials within a prefabricated system on a previously occupied site, alongside improved repairability and reuse potential. Scenario 4 represents a higher level of circularity, involving adaptive reuse of an existing building combined with modular design, extensive use of bio-based and remanufactured materials, and full integration of disassembly and take-back systems.

3.3.3 Eval 3: sensitivity analysis (ex post). To further assess robustness, a sensitivity analysis was conducted using the Nominal Range Sensitivity Analysis (NRSA) method, which

Table 5. Four case scenarios-definitions and differences regarding key CE parameters

Feature	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Site condition	New/undeveloped site	New/undeveloped site	Repurposed land (previous residential site)	Previously occupied site
Structural system	*In-situ* reinforced concrete frame	Prefabricated steel frame	Prefabricated glulam timber frame	Modular reuse of existing building
Foundation material	0% recycled steel, no recycled concrete	60% recycled steel, 3% recycled concrete	90% recycled steel, 3% recycled concrete	100% reused components (where applicable)
Wall assembly	Brick cladding, cement mortar	Steel sandwich panels, steel cladding	OSB, glulam, bio-based hempcrete	OSB and glulam, timber cladding
Insulation material	Glass wool (not disassemblable)	Mineral rock wool (disassemblable)	Bio-based sprayed hempcrete	Sheep's wool batts (80% recycled)
Flooring	Nylon carpet, ceramic tiles	Nylon carpet (25% recycled), ceramic tile	Timber flooring, ceramic tiles (70% recycled)	Cork flooring (100% reused)
Design for disassembly	No modularity or adaptability (welded joints)	Some prefabrication, bolted steel joints	Modular glulam structure with repair-friendly connectors	Modular components with dry mechanical connections
Reuse and recycling	Minimal recycling (steel only), no reuse	Recycled content in steel and some finishes	High recycled content, bio-based and decomposable materials	Highest reuse/recycled materials across components
Waste scenarios	Most waste landfilled	Most waste landfilled, steel recycled	Reduced waste via prefabrication and bio-based decomposition	Take-back systems in place, reuse and recycling prioritized
Flexibility/Extendibility	None	Limited (some replaceable parts)	Designed for future repairs and replacements	Highly flexible, disassemblable, and reconfigurable

Source(s): Authors' own work

evaluates the influence of input variations on model outputs (Christopher Frey and Patil, 2002). Nine key KPIs were selected based on their relevance and importance derived from Mani *et al*. (2026b), including recycled materials, durability, reused material output, energy renewability, water circularity, CO_2 emissions, disassembly, material health, and refuse unnecessary new construction. Each KPI was varied within a defined range (lower value = 0.1, nominal value = 0.5, and upper value = 0.9), while keeping other variables constant. This approach enabled the identification of the most influential KPIs and verified the stability and consistency of the model under varying assumptions, thereby strengthening its robustness. In addition, a sensitivity analysis was conducted on the KPI weights derived through the FAHP method to assess the robustness of the model with respect to expert judgment. A similar approach was adopted by varying the selected five KPI weights within a defined range.

4. BCP model development

Figure 2 presents the BCP model, showing the integration of KPIs across all building levels and life cycle phases, along with the main formulas. The conceptual foundation of the BCP model is grounded in CE principles and strategies, systems thinking, and lifecycle-based assessment principles. At its core, the model operationalizes CE strategies (10R hierarchy and design strategies) by translating them into measurable KPIs that capture resource preservation, value retention, and waste minimization across the building lifecycle. As discussed in section 3.1, the framework builds on MCI and WBCI, while addressing their limitations through a more comprehensive and integrated structure. The framework aligns with lifecycle thinking, incorporating all phases defined in BS-ISO-EN-15978 (2011): extraction/manufacturing (A1-A3), construction/assembly (A4-A5), use/operation (B1-B5), EOL stages (C1-C3), and beyond-system-boundary impacts (D). Existing metrics often overlook key stages, particularly A1, A2/A4 transportation, and operational energy (B6) and water (B7), even though these phases contribute significantly to emissions and resource use (Nässén *et al.*, 2007). Unlike purely material-centric approaches, the BCP model integrates environmental performance (e.g. CO_2 emissions, energy renewability, and water circularity) with circular design strategies such as repairability and modularity, thereby linking circularity with broader sustainability and resource efficiency objectives.

Multiple components interact within *systems/layers*, following Brand (1995) “Shearing Layers”: site, structure, skin, services, space plan, and stuff (with Stuff excluded due to limited

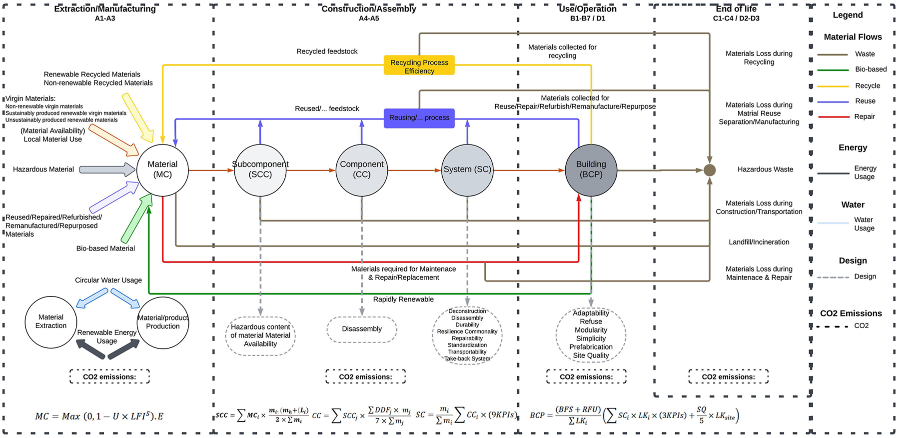

Figure 2. BCP model design and main formulas. Source: Authors’ own work

relevance to design circularity). Each system has distinct materials, lifespans, and replacement frequencies, interacting at the building level to create a structure that fulfills its purpose. This hierarchical framework forms the basis of BCP. This enables circularity to be assessed not only at the material level but across interconnected building layers, reflecting real-world system behavior. ISO 20887 (2020) recommends applying design guidelines (disassembly and adaptability) across building, system, element, component, subcomponent, and material. WBCI uses four levels, and Anastasiades *et al.* (2023) use five. To address the first gap (comprehensive whole-building assessment) while managing complexity, BCP evaluates circularity across five levels. Together, these theoretical foundations support the holistic and decision-oriented BCP conceptual model capable of capturing the complexity of circularity in building design. This section presents the main formulas and enhancements to MCI and WBCI, while sub-formulas appear in Appendix Table A2.

4.1 Material level circularity (MC)

As shown in Figure 3, BCP first calculates material circularity (MC), based on MCI. MCI is calculated using the Linear Flow Index (LFI) and Utility of the product (U), as outlined in Eq. (1).

$$MCI = Max\left(0, 1 - U \times LFI\right) \qquad (1)$$

LFI represents the quantity of material that follows a linear flow, while U measures how long and intensively a product is used compared to the average product of the same type. Adjustments in BCP incorporate criticality and environmental performance (Eq. 2).

$$MC = Max\left(0, 1 - U \times LFI^{S}\right).E \qquad (2)$$

Utility Factor (U). U is determined by the Technical Life (TL) and Functional Lifetime (FL) of a material or product. TL refers to the number of years a material remains functional before failure, while FL represents the period before a material becomes obsolete due to evolving needs (e.g. aesthetics, economic shifts, or user preferences). Since a product's useful life

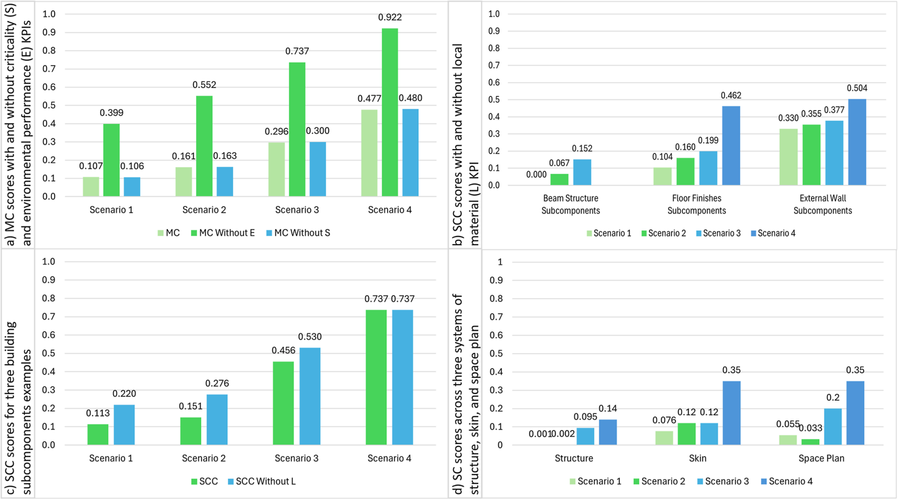

Figure 3. Circularity scores across all scenarios and all levels. Source: Authors' own work

depends on both factors, the shorter of TL or FL is used in the calculation (Khadim *et al.*, 2023) (Eq. 3):

$$U = \frac{0.9}{\min\left(FL, TL\right)/L_{brand}} \tag{3}$$

Here, L_{brand} represents the lifespan of different systems as specified in Brand (1995), and the value 0.9 is a constant derived from the utility equation in the original MCI model.

Linear Flow Indicator (LFI). LFI measures the linearity of material use based on virgin total mass (M'), virgin material input (V_{nr}), and material wastage (W), outlined in Eq. (4).

$$LFI = \frac{V_{nr} + W}{2M'} \tag{4}$$

(1) Total mass of material (M'). While the original MCI considers only the mass of material that ends as a product, BCP adopts a more holistic approach from WBCI, which considers additional materials required during the construction phase and maintenance and repairs, denoted as M'. M' includes the additional material required during construction (M_{cl}) and maintenance and repairs (M_{rm}), as explained in Eq. (5).

$$M' = M + M_{cl} + M_{rm} \tag{5}$$

M_{rm} is calculated considering the regular maintenance cycle (RM) and the mass of materials required for one cycle (Eq. 6). Khadim *et al.* (2023) consider the RM compared to the TL of the material. However, BCP considers the complete replacement in addition to the required repair and maintenance during the lifespan of the building.

The formula for M_{cl} is shown in Table A2 in the Appendix.

$$M_{rm} = \frac{TL}{RM} \times M_{RM} + \frac{Building's\ lifespan}{TL} \times M \tag{6}$$

$$(\text{if TL} < \text{Building's lifespan})$$

(2) Virgin input (V_{nr}). WBCI considers four material scenarios: virgin (V), reused (Fu), recycled (Fr), and bio-based (Fb), considering both CE cycles to address the third gap. However, as shown in Figure 3, BCP expands beyond this by incorporating additional material input scenarios, including non-renewable virgin (V_{nr}), renewable virgin (V_r), repaired (F_{rep}), refurbished (F_{fb}), remanufactured (F_{mu}), and repurposed (F_{pr}), as outlined in Eq. (7). This comprehensive approach ensures alignment with the 10R hierarchy of CE strategies, addressing last gap identified in Section 2. The last four scenarios have also been applied in the BC assessment method developed by Zhang *et al.* (2021a, b).

$$V_{nr} = M'\left(1 - V_r - F_r - F_u - F_{rep} - F_{fb} - F_{mu} - F_{pr} - F_b\right) \tag{7}$$

(3) Material Waste (W). At EOL, significant waste is generated, with some materials going to landfills and others being collected for energy production (Ellen MacArthur and Granta, 2019). Material losses occur throughout various stages, including construction, transportation, extraction, recycling, and reusing processes (Khadim *et al.*, 2022), all contribute to substantial emissions (ISO 14044, 2006). Previous methods have incorporated four waste scenarios: unrecoverable waste (W_O),

recycling (W_C), construction loss (W_{cl}), and maintenance and repairs waste (W_{rm}). In WBCI, it is assumed that no waste is generated during the reuse of building materials. However, material losses do occur during the separation (W_{ms}) and manufacturing process (W_{mn}) of material reusing, losses occur. BCP incorporates these losses, offering a more realistic approach. Additionally, a portion of material waste is classified as hazardous waste (W_H), which cannot be reintegrated into the material loop. BCP considers this hazardous amount, recognizing its significant environmental impact (Eq. 8).

$$W = W_O + W_C + W_{cl} + W_{rm} + W_H + W_{mn} + W_{ms} \tag{8}$$

Unrecoverable Waste (W_O) refers to the amount of waste going to landfill or energy recovery. The calculations for W_O and W_C are shown in Appendix Table A2. WBCI equates W_{cl} and W_{rm} to M_{cl} and M_{rm}, assuming the total mass of a building remains constant as maintenance materials replace existing ones. W_H is the amount of hazardous waste generated at EOL that should be minimized to zero (Baratsas *et al.*, 2021). Its values can be found in the EPDs. For assessing W_{mn} and W_{ms}, BCP uses the calculations proposed by Bracquené *et al.* (2020), as presented in Appendix Table A2.

Material Criticality/Availability Indicator (S). Material flow alone cannot fully capture material circularity, and the use of scarce natural materials should be minimized (Anastasiades *et al.*, 2023). To address this, BCP incorporates a material criticality indicator based on Surplus Ore Potential (SOP), which reflects how much extra ore must be extracted to obtain a resource defined by Vieira *et al.* (2017). Used in studies like ReCiPe-LCA (Huijbregts *et al.*, 2017) and CCI (Anastasiades *et al.*, 2023), BCP integrates it as an exponent in LFI calculation (Eq. 9). When materials contain rare constituents, their S_d value decreases, increasing LFI and reducing MCI, indicating lower circularity.

$$S_d = \sum_{q=1}^{s} f_{d,q}.min\left\{1;\ \frac{1}{SOP_q}\right\} \tag{9}$$

(1) $f_{d,q}$ is the fraction of constituent q in the element's finished material

(2) S is the total number of constituents in the finished material

Environmental Performance (E). During the material extraction and production, significant amounts of water and energy are consumed, alongside substantial emissions. To address the fourth gap, BCP incorporates indicator E (Figure 3) to assess the environmental aspects of buildings, including environmental impacts (E′), energy renewability (EN), and water circularity (W), ensuring comprehensive circularity assessment (ISO 59020, 2023). BCP uses this calculation similar to MDI (Mesa *et al.*, 2020) integrating environmental impacts with material durability (Eq. 10). Sub-formulas for These KPIs appear in Appendix Table A2.

$$E = E' \times 0.235 + EN \times 0.442 + W \times 0.323 \tag{10}$$

4.2 Subcomponent level circularity (SCC)

SCC normalizes MC scores based on material mass contributions (m_i) (Figure 3). BCP improves this assessment by incorporating Hazardous Content indicator (Eq. 11), measuring the proportion of non-hazardous material, inspired by D-DAS (Akanbi *et al.*, 2019b), as shown in Eq. (11). Products containing >0.1% Substance of Very High Concern (SVHC) under EU-REACH are flagged as having hazardous content (Klaschka, 2017). Its values can be found in the EPDs.

$$SCC = \sum MC_i \times \frac{m_i . m_h}{\sum m_i} \tag{11}$$

ISO 20887 (2020) emphasizes circular design strategies like adaptability and disassembly, and studies show that poor design contributes significantly to on-site construction waste (Amaral *et al.*, 2020). While WBCI includes two design KPIs: "disassembly" and "adaptability," effective assessment requires considering disassembly and other design strategies across all levels. To enhance comprehensiveness, BCP incorporates ten additional design-related KPIs to fulfill the fourth gap, as detailed in next sections.

4.3 Component level circularity (CC)

As shown in Figure 3, CC aggregates SCCs scores and incorporates disassembly KPI as defined by Durmisevic (2005) and adopted in previous BCIs (Anastasiades *et al.*, 2023; Khadim *et al.*, 2023; Madaster, 2018). The BCP integrates the 7 DDFs from Durmisevic (2005), which were derived from connection disassembly characteristics (Eq. 12). A mass-based normalization factor adjusts for the subcomponent's weight within the component.

$$CC = \sum SCC_j \times \frac{\sum DDF_j \times m_j}{7 \times \sum m_j} \tag{12}$$

4.4 System level circularity (SC)

SC normalizes CC scores across components using mass as an additional normalization factor and integrates nine system-level design KPIs (Eq. 13), including Disassembly (D), Deconstruction (DE), Resilience/Longevity (Re), Durability (D), Transportability (T), Standardization (*N*), Commonality (C), Repairability (RP), and Take-back systems (TB).

$$\begin{aligned} SC = \frac{m_i}{\sum m_i} \sum CC_i \times (\mathrm{C}D_i \times 0.093 + DE_i \times 0.071 + Re_i \times 0.172 + N_i \times 0.096 + C_i \times 0.042 \\ + T_i \times 0.066 + RP_i \times 0.152 + D_i \times 0.171 + TB_i \times 0.137) \end{aligned} \tag{13}$$

The equations for these KPIs are provided in Appendix Table A2. Disassembly is calculated similar to the previous level (Eq. 12). DE measures the ability to remove and reuse structural elements, while Re assesses a system's capacity to withstand and recover from disruptions; (O'Grady *et al.*, 2021); both follow formulas from O'Grady *et al.* (2021). T evaluates how easily components can be moved based on size, weight, and access to transport networks, using the method from Coenen *et al.* (2021). TB indicates practical recyclability through manufacturer programs following a five-level rating scale developed by Struck and Flamme (2023) with scores normalized to 0–1 for integration with other KPIs in BCP. RP, based on Ruiz-Pastor and Mesa (2023), combines relative functional importance and overall repairability. Durability, following Akanbi *et al.* (2019a) and Mesa and González-Quiroga (2023), averages geometric and material durability to reflect structural and material resistance.

4.5 Building circularity performance (BCP)

Building-level circularity can be normalized by mass, value, importance (LK), or embodied energy, but using mass alone can skew results by overweighting structure and skin and undervaluing services (Khadim *et al.*, 2023). BCP also includes the reuse of existing usable surfaces (RFU), supporting adaptive reuse, which reduces new construction, resource use, and emissions (Foster, 2020). Adaptability and flexibility are essential for extending building life (Khadim *et al.*, 2023), and modular, simple, and prefabricated components further enhance circularity (Mesa and González-Quiroga, 2023). Site quality is also considered using BREEAM's "Site Selection" criteria (BRE Global, 2021). BCP is calculated by normalizing the SC of all systems (Figure 3), incorporating Modularity (M), Simplicity (S), Prefabrication (FB), LK, Building Flexibility Score (BFS), RFU, and Site Quality (SQ) (Eq. 14).

$$BBCP = \frac{(BFS \times 0.521 + RFU \times 0.479)}{\sum LK_i}\left(\sum SC_i \times LK_i \times (M_i \times 0.421 + S_i \times 0.222 + FB_i \times 0.358) + \frac{SQ}{5} \times LK_{site}\right) \quad (14)$$

The formulas and values for these KPIs are presented in Appendix Table A2. LK_i represents the importance level of each system. BFS is adapted from the Flex 4.0 method (Geraedts, 2016), using 12 sub-indicators to determine the flexibility classes which are adjusted in BCP. RFU measures the share of reused surface area to reduce new material use and is extended across all building systems from the original framework using appropriate units (Arup and Ellen MacArthur, 2022). SQ is evaluated using BREEAM "Site Selection" criteria (BRE Global, 2021), adopted by CCS (Fagone *et al.*, 2023), prioritizing contaminated or previously developed land. Since the "Previously Occupied Land" component overlaps with RFU, it is excluded here.

5. Results and discussion

This section presents and discusses the circularity outcomes for the four case scenarios across all BCP levels, the focus group session, and the sensitivity analysis. The model's generalizability is supported by the scenario-based evaluation, which tests the model under varying design and material conditions. Moreover, the BCP is developed as a design-oriented framework based on general CE principles and validated KPIs, rather than case-specific inputs, supporting its applicability across different building types and contexts (Sein *et al.*, 2011; Gregor and Jones, 2007). The findings highlight the effectiveness of various CE strategies in improving circularity performance, demonstrate the advantages of BCP compared to previous frameworks, and validate its robustness.

5.1 BCP model applicability (demonstration)

The demonstration phase confirmed the applicability and functionality of the BCP model when applied to the case study. The model was successfully implemented across all building levels, enabling the calculation of circularity performance based on the defined KPIs and data inputs. The resulting circularity scores and trends are consistent with those reported for Scenario 1 in the evaluation phase. Therefore, to avoid repetition, detailed results are presented in Section 5.3 (Eval 2). These results were then used as input for the subsequent focus group evaluation to support expert discussion and evaluation of the model.

5.2 BCP refinement through focus group (eval 1)

Expert feedback was structured around validity, reliability, and utility.

(1) Validity: Experts recommended adding material elimination strategy at the material level, but this was considered redundant as it is already addressed at the building level through RFU KPI and reuse-related KPIs. They also suggested including a KPI for "local material use." As one expert suggested: "*It's hard to find or quantify local materials use . . . LBC (Living Building Challenge) uses a distance-radius method.*" Following the Living Building Challenge distance-based approach (International Living Future Institute, 2024), a new locality KPI (L) was proposed at the Sub-component level to capture local material use (Eq. 15).

For Oceania countries:

$$L_i = \begin{cases} 1, if\ d_i \leq 2000\,km \\ 0, if\ d_i > 2000\,km \end{cases}$$

For other countries:

$$L_i = \begin{cases} 1, if\ d_i \leq 500\,km \\ 0, if\ d_i > 500\,km \end{cases} \tag{15}$$

Accordingly, the refined SCC formula is outlined in Eq. (16).

$$SCC = \sum MC_i \times \frac{m_i \times (m_h + L_i)}{2 \times \sum m_i} \tag{16}$$

(2) Reliability: Concerns were raised about static and assumption-based datasets (e.g. EPDs) and unreliable recycling efficiency rates. However, EPDs are standardized documents endorsed by the ILCD System as reliable LCA sources, and they are increasingly adopted in the construction industry (Moré *et al.*, 2022; Soust-Verdaguer *et al.*, 2022; Waldman *et al.*, 2020) and recycling efficiency rates can be improved as more reliable datasets become available in the future. Experts also highlighted the risk of greenwashing, where users might tweak inputs to appear more circular. To mitigate this risk, future improvements include automated data inputs and transparency features (e.g. pre-filled EPD values) in digital platforms. As one expert noted, "*If you had a digital tool, when someone selects a material, it can automatically fill in the EPD data – like how One Click LCA does it – that would remove a lot of the inconsistency and risk of people putting in wrong or biased data.*"

(3) Utility: To enhance adoption, experts proposed a tiered BCP structure for future development with preliminary (based on high-impact KPIs) and advanced (comprehensive) to suit different user needs. As two experts noted, "*It would be helpful if the tool can be tiered so that users with different goals—say a marketing team vs a certifier—can all use it,*" and "*Offering different entry levels but the same core method increases adoption chances.*" They also noted the need for flexibility as industry data evolves, noting that the non-weighted BCP version allows easier adaptation. Finally, experts stressed the importance of communicating BCP's value to developers. The BCP model aims to support architects, designers, project managers, and policymakers in promoting CE practices.

5.3 BCP application in the case scenarios results and comparison with previous metrics (eval 2)

The refined version of BCP was applied to the four defined case studies to validate its applicability. The results demonstrate a clear and progressive increase in circularity performance from Scenario 1 (linear) to Scenario 4 (highly circular), confirming the BCP model's ability to distinguish among varying levels of circularity. Supporting Excel data sheets are available upon request.

5.3.1 Material circularity (MC). At the material level, MC scores were calculated based on U, LFI, S, and E. As shown in Figure 3 (a), MC scores increased from 0.107 in Scenario 1 to 0.477 in Scenario 4, reflecting the transition from virgin materials with limited recovery potential to recycled, bio-based, and reused materials. Scenario 2 showed a moderate improvement (MC = 0.161) through partial use of recycled content, while Scenario 3 (MC = 0.296) further benefited from the introduction of bio-based materials.

Two sensitivity tests were performed to compare the original MC with the exclusion of criticality (S) and environmental performance (E) KPIs. This analysis further validates BCP's advancement compared to MCI and WBCI. Results indicated that excluding E significantly increased MC values (e.g. from 0.161 to 0.552 in Scenario 2), whereas excluding S had minimal effect, confirming the strong influence of environmental indicators on circularity outcomes. This is because environmental indicators directly influence the material-level calculation and propagate through higher levels of the model, amplifying their impact on overall circularity outcomes. This demonstrates that circularity performance is not solely governed by material flows, but is strongly influenced by environmental and lifecycle-related factors, reinforcing the need to integrate environmental performance within circularity assessment rather than treating it as a separate dimension. It also indicates that conventional material-focused metrics may overestimate circularity by neglecting these embedded environmental effects.

5.3.2 Subcomponent circularity (SCC). At the subcomponent level, circularity performance improved consistently with changes in material selection and design strategies. Subcomponents incorporating renewable and non-hazardous materials, such as timber and cork, achieved higher SCC scores compared to conventional materials. For instance, as illustrated in Figure 3 (b), structural elements progressed from SCC = 0 (*in situ* concrete) in Scenario 1 to 0.162 (glulam timber) in Scenario 3, while floor finishes improved from 0.104 (ceramic tiles) to 0.462 (cork flooring). The inclusion of the locality KPI (L) further refined the results (in Figure 3 (c)), reducing SCC values in early scenarios due to long transport distances (e.g. 0.113 to 0.220 in Scenario 1 without L), while having no impact in Scenario 4, where all materials were locally sourced. This behavior reflects how locality introduces an additional constraint on material sourcing, penalizing otherwise high-performing materials when transport distances are large. This indicates that circularity is constrained not only by material properties but also by supply chain and sourcing distances, expanding the scope of circularity assessment beyond material composition. This level of assessment, largely absent from previous metrics, aligns with ISO 20887 (2020) and highlights the importance of subcomponent-level decisions, representing the advancement of this study. Consistent with Anastasiades *et al.* (2023), the results confirm that subcomponents can either enhance or undermine the circularity score.

5.3.3 Component circularity (CC). At the component level, circularity depends on the disassembly potential of subcomponents. Components made of easily disassembled subcomponents achieved higher CC scores (Figure 4).

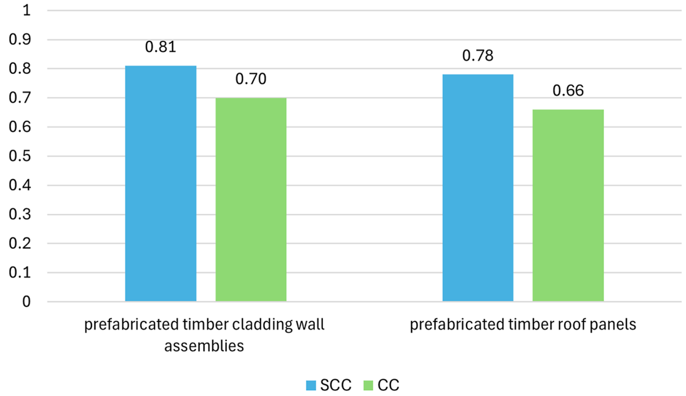

Figure 4. Comparison of SCC and CC scores for the same subcomponent and component. Source: Authors' own work

As shown in Figure 4, although prefabricated timber cladding walls achieved a high SCC (0.81), their CC score decreased to 0.70 due to limited disassembly potential. A similar reduction was observed for prefabricated timber roof panels (SCC = 0.78; CC = 0.66). The results demonstrate that material circularity alone does not guarantee high overall circularity if disassembly is constrained. This occurs because disassembly is evaluated at the component level, where connection types and assembly methods constrain reuse potential regardless of material performance. This highlights a critical dependency between material selection and design configuration, where circularity outcomes are constrained by how components are assembled rather than what they are made of. It further demonstrates that without design for disassembly, material-level improvements cannot be fully realized at higher levels of the building system. Previous studies similarly emphasize the role of joint accessibility and connection reversibility (Durmisevic, 2005; O'Grady *et al.*, 2021). Unlike MCI and WBCI, which do not explicitly address assembly constraints, BCP quantitatively captures the transition from material efficiency to component reusability to maintain circularity at this level, enabling reuse throughout the building's lifecycle.

5.3.4 System circularity (SC). System-level circularity is influenced by multiple KPIs, including disassembly, deconstruction, durability, repairability, and transportability of components. As shown in Figure 3 (d), scenario 1 exhibited very low SC values, particularly for the structure (SC = 0.001), due to the dominance of *in situ* construction and lack of disassembly and reuse potential. Scenario 2 showed only marginal improvements, while Scenario 3 demonstrated a notable shift, with the space plan achieving the highest SC (0.20) due to the introduction of prefabricated and reusable systems. Scenario 4 achieved the highest performance, with both the skin and space plan layers reaching SC = 0.35, and the structure improving to 0.14. This improvement is driven by the integration of modularity, prefabrication, and repairability, which enhance the performance of multiple KPIs simultaneously at the system level. This reflects the cumulative effect of integrating multiple circular design strategies, where improvements in modularity, prefabrication, and repairability simultaneously enhance the circularity performance. Such behavior confirms that circularity is an emergent property of system configuration rather than a direct outcome of isolated indicators.

Overall, these results show that system-level circularity is enhanced when modularity, disassembly, and repairability are embedded in design. These findings also demonstrate how the BCP model can support design decision-making by identifying high-impact strategies such as modularity and disassembly at early project stages. BCP therefore demonstrates its value in comparing circularity across building layers and in identifying which strategies influence system-level outcomes. Compared to earlier models, BCP offers a more comprehensive system-level assessment. While BCI and WBCI primarily consider disassembly, and 3DR incorporates a limited set of additional indicators, BCP integrates a broader range of CE strategies, enabling clearer identification of system-level trade-offs.

5.3.5 Building circularity performance (BCP). At the building level, the overall BCP score increased substantially from 0.008 in Scenario 1 to 0.700 in Scenario 4, demonstrating the cumulative impact of material, component, and system-level improvements. Scenario 1 achieved a very low circularity level, while scenario 4 achieved a good circularity performance according to Table 2. Scenario 2 showed only a slight increase (0.011), indicating that partial recycling and prefabrication alone are insufficient to significantly enhance circularity. A more substantial improvement was observed in Scenario 3 (0.119), driven by the integration of bio-based materials and disassembly principles. The sharp increase in Scenario 4 confirms that circularity is maximized when material strategies are combined with design interventions, such as modularity, prefabrication, and repairability. This pattern indicates that circularity performance emerges from the combined interaction of material, design, and system-level strategies rather than isolated improvements in individual indicators.

Overall, these findings confirm that building circularity is not simply the aggregation of material or component choices but is strongly shaped by design strategies. Compared with earlier models such as MCI and WBCI, BCP advances circularity by integrating design-related KPIs and environmental KPIs into a single weighted framework, capturing interactions across building levels more realistically. Furthermore, the model avoids inflated circularity scores from isolated interventions, demonstrating that improvements must be structurally embedded within the building design to influence overall performance. This strengthens the analytical validity of the BCP model by ensuring that results reflect realistic design behavior rather than simplified or isolated parameter changes. The consistent and logical progression of results across scenarios demonstrates the robustness of the BCP model and its ability to support comparative evaluation of alternative design configurations.

5.4 Assessing BCP robustness: sensitivity analysis of key KPIs and their weights (eval 3)

A sensitivity analysis (NRSA) was conducted to assess the robustness of the BCP model to variations in key KPIs and their weights. The results show that the model responds logically and consistently to input changes, with sensitivity increasing as scenarios become more circular (Figure 5 (a)). In Scenario 1, the BCP score remained close to zero regardless of input variation, indicating limited responsiveness in highly linear configurations. In contrast, Scenarios 2–4 showed progressively higher sensitivity, confirming that the model better

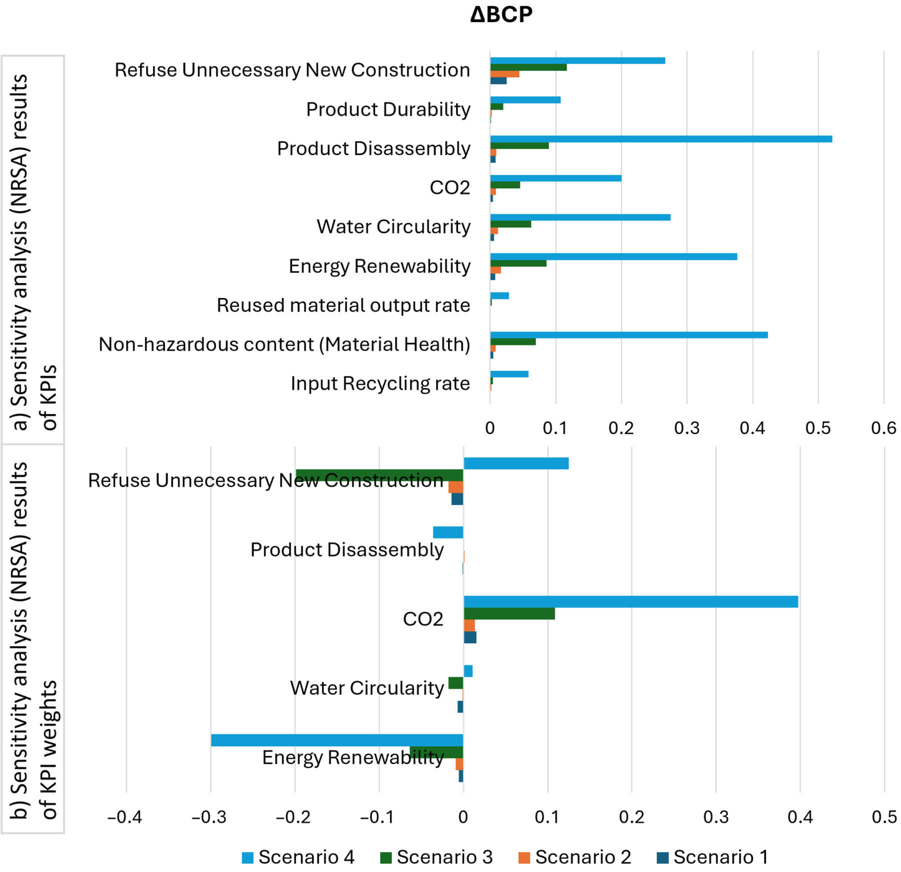

Figure 5. Sensitivity analysis (NRSA) of selected KPIs and their weights results across all four scenarios.
Source: Authors' own work

differentiates performance as circular strategies are introduced. This behavior indicates that the model becomes more responsive as circular design features are embedded, allowing performance differences to emerge more clearly across scenarios.

Among the tested KPIs, the largest impacts were observed in Scenario 4, where component disassembly (ΔBCP $\approx$ 0.52) and material health (ΔBCP $\approx$ 0.42) produced the greatest changes in circularity scores. Environmental indicators, including energy renewability (ΔBCP $\approx$ 0.38), water circularity (ΔBCP $\approx$ 0.28), and CO_2 emissions (ΔBCP $\approx$ 0.20), also showed strong influence, while material flow indicators such as recycling rate and reused output had relatively minor effects. In intermediate scenarios (e.g. Scenario 3), refuse unnecessary new construction (ΔBCP $\approx$ 0.12) and disassembly emerged as key drivers of performance.

Sensitivity analysis of KPI weights further confirmed the model's robustness. Although variations in weights led to changes in absolute BCP scores, these remained within a bounded range (approximately -0.30 to $+0.40$), and the ranking of scenarios remained unchanged across all cases (Figure 5 (b)). This demonstrates that the BCP model is not overly sensitive to weighting assumptions and provides stable and reliable comparative results. Negative ΔBCP values indicate that increasing the weight of a KPI leads to a reduction in the overall BCP score. This occurs when the evaluated scenario performs relatively poorly in that indicator, and higher weighting amplifies its influence within the aggregation. This behavior is expected and reflects the model's ability to penalize underperforming aspects more strongly when their importance increases. Importantly, these responses remained gradual and bounded, indicating controlled sensitivity rather than instability in the model.

It should be noted that several model inputs are derived from secondary databases and assumed values (e.g. EPDs, material lifespans, and recycling rates), which may introduce uncertainty into the results. To address this, sensitivity analyses results show that, although variations in inputs lead to changes in absolute BCP scores, these changes remain within bounded ranges and do not alter the overall trends or scenario rankings. This indicates that the model is not overly sensitive to input assumptions and provides robust comparative results. Overall, the findings confirm that the BCP model is both responsive and robust, capturing the increasing impact of circular strategies while maintaining consistent and interpretable outcomes across different design scenarios. The combined results of KPI and weight sensitivity analyses demonstrate that the model achieves a balance between sensitivity and stability, where it is sufficiently responsive to detect meaningful changes while remaining resistant to instability caused by input uncertainty. This balance is critical for practical application, as it ensures reliable decision support without overreacting to minor variations in input data or expert judgment.

6. Conclusion, implications, and future work

This study introduced the Building Circularity Performance (BCP) model, a comprehensive, multi-level framework that quantifies building circularity. Extending established metrics like MCI and WBCI, the BCP integrates 52 validated and weighted KPIs, aligned with ISO 20887 and ISO 59020. BCP addresses key CE principles while also integrating often overlooked aspects of circular building strategies, covering material flows, energy renewability, water circularity, CO_2 emissions, and design strategies.

The main contributions of this study are threefold: (1) it develops a structured and multi-level model that operationalizes both widely used and previously neglected CE aspects across five building levels (materials, subcomponents, components, systems, and the whole building); (2) it identifies the most and least influential CE strategies in assessing circularity performance; and (3) it reflects the expectations of industry professionals regarding practical building circularity assessment. BCP incorporates several new and previously overlooked CE dimensions, including environmental performance KPIs (energy renewability, water circularity, and CO_2 emissions), circular building design strategies such as modularity and prefabrication, and additional considerations like refuse unnecessary new construction, site quality, hazardous materials and waste, and use of local materials. These advancements enable a more realistic and actionable approach to circularity assessment compared to previous models that tend to focus narrowly on material flows. Importantly, the results demonstrate that circularity is not driven by isolated indicators but emerges from the interaction of material, environmental, and design-related factors. This reinforces the need for integrated assessment approaches.

The focus group evaluation reinforced the model's practical value and identified refinements, including integrating local material sourcing, improving automation through pre-filled EPD data, and developing a tiered framework (preliminary and advanced) to increase accessibility for diverse users. The case study and evaluation results demonstrated the model's ability to assess circularity across all building levels and identify critical improvement areas. Renewable and bio-based materials such as sheep's wool insulation and reclaimed timber achieved the highest material circularity scores, while non-renewable materials like float glass and aluminum performed lower. Design strategies emphasizing modularity, repairability, and adaptability were most influential in raising overall circularity. The progressive improvement observed across scenarios confirms that circularity develops incrementally and non-linearly, requiring the coordinated implementation of multiple strategies rather than incremental or single-dimension interventions. The sensitivity analyses further confirm that the model achieves a balance between responsiveness and stability, ensuring that results remain robust under variations in inputs and weighting assumptions. This is critical for its reliability in real-world decision-making contexts.

Ultimately, the BCP model makes significant theoretical and practical contributions to building circularity assessment. For the first time, this study integrates KPIs with their relative weights, reflecting their importance and enabling a prioritized, decision-oriented evaluation approach.

From an industry perspective, the model provides a structured basis for defining measurable circularity targets and benchmarks. BCP serves as a practical tool for designers, architects, clients, and project managers to implement CE principles from the early design stages, supporting informed decision-making, resource efficiency, and performance benchmarking. For example, developers and clients can apply it to guide investment decisions and sustainability reporting. From a policy perspective, it can support regulatory frameworks, certification systems, and procurement processes by enabling performance-based requirements (e.g. minimum circularity scores or KPI thresholds). For instance, policymakers can use the model to prioritize high-impact strategies such as adaptability and modularity. In practice, the model can be integrated into existing workflows by linking with BIM-based material databases, LCA tools, or digital material passports, enabling automated data input and real-time circularity assessment during the design process. Such integration would facilitate early-stage decision-making, allowing stakeholders to compare alternative design options and optimize circularity performance before construction begins.

In terms of societal impact, the BCP model contributes to the operationalization of Sustainable Development Goals, particularly SDG (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action), by translating high-level sustainability objectives into measurable design-stage actions. Rather than remaining conceptual, these contributions are realized through practical applications such as reducing material demand through reuse (RFU). This improves resource efficiency through modular construction, and lowering emissions via renewable energy integration.

The model's adaptability allows potential integration of future circularity KPIs, enhancing their coverage of circularity performance in the building sector. However, this flexibility applies only to the non-weighted version of BCP, as the weighted version requires a fixed set of KPIs for comparative analysis. Future research should address these limitations by developing dynamic weighting approaches that allow the integration of new KPIs without compromising comparability. Another concern is the potential for input manipulation to inflate circularity scores. The development of a digital BCP platform with automated data integration (e.g. pre-filled EPD databases and BIM-linked inputs) would reduce user bias and enhance transparency. Future research may also consider structuring the BCP into two tiers—preliminary and advanced—to support broader adoption by users with different goals. The preliminary tier could focus on high-impact KPIs for rapid assessment, while the advanced tier could provide a comprehensive evaluation for detailed analysis.

Ethical statement

This research involved human participants and received ethical approval from the Deakin University Human Research Ethics Committee (Approval No. SEBE-2023–66). All expert participants provided informed consent prior to their participation in the study.

AI generative

AI-based tool (Grammarly) was used to support language and grammar editing and clarity of expression across the manuscript. All conceptual development, data interpretation, and scholarly content were developed by the authors.

Appendix

Table A1. Design information for the sample building

Design parameters	Details	Design parameters	Details
Height (above ground)	2.8 m	Width	16 m
Reference region	International reference building (EN15804+A2) v2024.1	Depth	8 m
Building type	One-dwelling buildings	Internal floor height	2.5 m
Assessment period	50 years	Maximum column spacing distance	6 m
Gross floor area (GFA) (m^2)	300 m^2	Load bearing internal walls	0%
Number of above ground floors	1	Number of staircases	0
Number of underground heated floors	0	Gross internal floor area (GIFA)	128 m^2
Envelope thickness	0	Maximum building depth	8 m
Floor thickness	0.3 m	Shape Efficiency Factor	1.1
External window ratio	0.3 m	Total number of floors	1
		Maximum window ratio	0.5

Source(s): Authors’ own work

Table A2. The relative equations and descriptions for KPIs

Level	KPI	Formula	Data source	Assumption/ Limitation	Reference
Material	E′ (CO_2 emissions)	$E' = 1 - \frac{C}{C_{max}}$ C’: the CO_2 of the case study C_{max}: maximum CO_2 possible within the material category	C: EPD C_{max}: EC3 tool	–	Mesa *et al.* (2020)
	EN (energy renewability)	$EN = \frac{Renewable\ energy\ (whole\ life\ cycle)}{Total\ energy\ consumption} \times 100\%$	EPD	–	WBCSD (2023)
	W (water circularity)	$W = \frac{\%\ circular\ water\ inflow + \%\ circular\ water\ outflow}{2}$ Where $\%\ circular\ water\ inflow = \frac{Q\ total\ circular\ water\ withdrawal}{Q\ total\ water\ withdrawal} \times 100\%$ $\%\ circular\ water\ outflow = \frac{Q\ total\ circular\ water\ discharge}{Q\ total\ water\ withdrawal} \times 100\%$	EPD	–	WBCSD (2023)
	M_{cl} (additional material required during construction)	$M_{cl} = Ø_l \times m_i$ $Ø_{l:}$ wastage percentage factor for material	One Click LCA	–	Khadim *et al.* (2023)
	W_O (Unrecoverable Waste)	$W_O = M(1 - C_r - C_u - C_b - C_e)$ $C_{r:}$ fractions of material collected for recycling $C_{u:}$ fractions of material collected for reuse $C_{b:}$ fractions of material collected for bio decomposition $C_{e:}$ fractions of material collected for sustained production of biological material for energy recovery	EPD	Composting applies only to non-toxic biological materials that meet compostable standard	Ellen MacArthur and Granta (2019)
	W_C (recycling waste)	$W_C = M(1 - E_C)C_r$ $E_{C:}$ efficiency of the recycling process	Literature (Krausmann *et al.*, 2017)	–	Ellen MacArthur and Granta (2019)

(*continued*)

Table A2. Continued

Level	KPI	Formula		Data source	Assumption/ Limitation	Reference
	W_{mn} (manufacturing loss)	$W_{mn} = W_{fp} + W_{cp}$ Where $W_{fp} = \frac{(1-F_u)M}{E_{fp}E_{cp}}(1-E_{fp})(1-C_{fp})$ $W_{cp} = \frac{(1-F_u)M}{E_{cp}}(1-E_{cp})(1-C_{cp})$ C_{fp} and C_{cp}: fractions of material losses that are recovered as useful recycled material E_{fp}: efficiency of feedstock production E_{cp}: efficiency of component production		Literature (Bracquené *et al.*, 2020)	–	Bracquené *et al.* (2020)
	W_{ms} (material separation loss)	$W_{ms} = M(1-E_{ms})C_r$ E_{ms}: efficiency of the material separation		Literature (Bracquené *et al.*, 2020)	–	Bracquené *et al.* (2020)
Component	CD (Disassembly)	$\frac{\sum DDF_j \times m_i}{7 \times \sum m_i}$ (A full list of DDFs and their corresponding fuzzy values will be provided based on request.)		Fuzzy values input by user	–	Durmisevic (2005)
System	DE (Deconstruction)	$DE = \frac{\sum (DEt_i \times DEm_i \times m_i)}{\sum m_i}$		Fuzzy values input by user	–	O'Grady *et al.* (2021)
		DEt Availability, dimensions, and types of tools required to deconstruct a building	No tool Hand tool Power tool Gas/pneumatic tool Hydraulic equipment	1 0.9 0.8 0.5 0.2		
		DEm People or equipment required to move components following deconstruction	One person: <20 kg Two people: <42 kg Hand trolley: <50 kg Forklift: <2,000 kg Crane: >2,000 kg	1 0.9 0.7 0.4 0.1		

(*continued*)

Table A2. Continued

Level	KPI	Formula		Data source	Assumption/ Limitation	Reference
	Re (Resilience)	$R = \frac{\sum(Re_i \times m_i)}{\sum m_i}$ $\mathrm{Re_i}$: resilience of component i $\mathrm{m_i}$: component i weight	Reusable indefinitely	1	–	O'Grady *et al.* (2021)
			Reusable up to three times	0.9		
			Reusable only once	0.7		
			Recyclable	0.6		
			Downcyclable	0.2		
			Disposable	0		
	T (Transportability)	$T = \frac{\sum(T_i \times m_i)}{\sum m_i}$ $\mathrm{m_i}$: component i weight	One-lane road and railway combined	1	–	Coenen *et al.* (2021)
			One-lane road only	0.8		
			Railway only	0.4		
			Barge along river	0.4		
			No available infrastructure	0		
	N (Standardization)	N/C Proportion of standardized components, N, with respect to the total number of components (C)		Input by user	–	Mesa and González-Quiroga (2023)
	C (Commonality)	COM/C The proportion of components that are common within the product family, COM, concerning the total number of components (C)		Input by user	–	Mesa and González-Quiroga (2023)

(*continued*)

Table A2. Continued

Level	KPI	Formula	Data source	Assumption/ Limitation	Reference
	TB (Take-back systems)	*There is a take-back system for . . .*		–	Struck and Flamme (2023)
		. . . the entire component, which reuses the component (if necessary, after reprocessing)	1		
		. . . the entire component, which reuses or recycles all parts of the component	0.8		
		. . . parts of the component, which reuses these parts (if necessary, after reprocessing)	0.6		
		. . . parts of the component, which (after reprocessing, if necessary) will be recycled	0.4		
		. . . construction waste generated during the construction of the component (pre-consumer), which is sent for recycling (if necessary, after reprocessing)	0.2		
		None of the above descriptions applies	0		
	RP (Repairability)	$RP = \sum Ro * RFI$ RFI: a subcomponent's significance within a component assembly Ro: component's structure-five key parameters (P1 to P5) (A detailed explanation of each parameter will be provided based on request.)	Fuzzy values input by user	–	Ruiz-Pastor and Mesa (2023)
	D (Durability)	$D = \frac{1}{2}(DG \times DM)$ Geometric Durability (DG) Material Durability (DM) (Scores and details for these parameters will be provided based on request.)	Fuzzy values input by user CES Selector database of GrantaDesign	–	Akanbi *et al.* (2019a), Mesa and González-Quiroga (2023)
Building	LKI (Level of Importance)	Site	0.1	–	Khadim *et al.* (2023)
		Structure	0.2		
		Skin	0.7		
		Services	0.8		
		Space Plan	0.9		

(*continued*)

Table A2. Continued

<table>
<tr><th>Level</th><th>KPI</th><th>Formula</th><th>Data source</th><th>Assumption/ Limitation</th><th>Reference</th></tr>
<tr><td></td><td>BFS (Adaptability/ Flexibility)</td><td colspan="2"><table>
<tr><th>Flexibility Class</th><th>FLEX 4.0 score</th><th>BCP score</th><th>BFS</th></tr>
<tr><td>1: Not flexible at all</td><td>12–48</td><td>9–14</td><td>0.2</td></tr>
<tr><td>2: Hardly flexible</td><td>49–85</td><td>15–20</td><td>0.7</td></tr>
<tr><td>3: Limited flexible</td><td>86–122</td><td>21–26</td><td>0.8</td></tr>
<tr><td>4: Very flexible</td><td>123–159</td><td>27–32</td><td>0.9</td></tr>
<tr><td>5: Excellent flexible</td><td>160–192</td><td>33–36</td><td>1</td></tr>
</table>(Sub-indicators and details will be provided based on request.)</td><td>–</td><td>Geraedts (2016)</td></tr>
<tr><td></td><td>RFU (Refuse unnecessary construction)</td><td>$RFU = \frac{Reused\ portion\ of\ System}{Total\ System\ Volume, Area, Mass}$
Reused Portion of System: amount (volume, area, mass) of the building system that is reused from the existing structure
Total System Volume, Area, Mass: total size of the system being evaluated</td><td>Drawings</td><td>–</td><td>Arup and Ellen Macarthur (2022), Ellen MacArthur and Granta (2019)</td></tr>
<tr><td></td><td>SQ (Site Quality)</td><td>$SQ = \left(\frac{B_i}{A}\times(-1)\right) + \left(\frac{B_{ii}}{A}\times(0)\right) + \left(\frac{B_{iii}}{A}\times(3)\right) + \left(\frac{B_{iv}}{A}\times(5)\right)$
• A is the total site area
• B_i is the area in its natural state
• B_{ii} is the area previously used as green or agricultural land
• B_{iii} is the area previously developed with structures or infrastructure
• B_{iv} is the area where remediation has been conducted or is planned</td><td>Drawings</td><td>–</td><td>Fagone et al. (2023)</td></tr>
<tr><td></td><td>M (Modularity)</td><td>M/C
Proportion of components considered as a module, M, with respect to the total number of components (C)</td><td>Input by user</td><td>–</td><td>Mesa and González-Quiroga (2023)</td></tr>
<tr><td></td><td>S (Simplicity)</td><td>$(1 - N * C)/C$
Measurement of the product complexity based on the number of components (C) and number of pieces (N)</td><td>Input by user</td><td>–</td><td>Mesa and González-Quiroga (2023)</td></tr>
<tr><td></td><td>FB (Prefabricated assemblies)</td><td>N_{fb}/C
Proportion of prefabricated assemblies, N_{fb}, with respect to the total number of components (C)</td><td>Input by user</td><td>–</td><td>Mesa and González-Quiroga (2023)</td></tr>
</table>

Source(s): Authors' own work

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Corresponding author
Gayani Karunasena can be contacted at: gayani.karunasena@deakin.edu.au