What to assess in circular buildings: key performance indicators for circular transformation

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

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Abstract

Purpose – This study addresses the critical gap in evaluating building circularity by developing a comprehensive framework of key performance indicators (KPIs). While circular economy (CE) principles are increasingly emphasized in building design, their adoption is hindered by the absence of standardized and prioritized KPIs across the building lifecycle.

Design/methodology/approach – A two-stage research design was employed. First, a systematic meta-synthesis of literature identified micro-level KPIs. Second, industry and academic experts validated and ranked them using a two-round fuzzy Delphi method and fuzzy analytical hierarchy process.

Findings – The study developed the Building Circularity KPI Framework (building circularity KPIs framework [$BC_{KPI}F$]), comprising 52 KPIs across six domains: material, waste, energy, water, CO_2 emissions and design. Findings highlight the need to incorporate overlooked circularity aspects such as energy, water, CO_2 emissions and design. $BC_{KPI}F$ shows a clear KPI prioritization: disassembly, refusing unnecessary new construction and material durability ranked highest overall. It also reveals prioritizations across different categories, reflecting preferred CE strategies for each category – for instance, reuse received the greatest weight for the material and waste categories.

Research limitations/implications – This study focuses on technical and environmental dimensions of building circularity. Economic and social aspects are excluded to allow a more focused and measurable assessment of circularity in buildings as CE focuses more narrowly on resource efficiency, material loops and system innovation.

Practical implications – Weighted KPIs guide practitioners in prioritizing interventions and selecting materials, technologies and design strategies. For policymakers, the results provide an evidence base for translating circular design strategies, such as reuse, modularity and deconstruction into regulatory benchmarks, procurement requirements and incentive mechanisms. The framework also supports progress toward multiple sustainable development goals.

Originality/value – This study advances the field by consolidating fragmented micro-level circularity KPIs into a comprehensive and weighted framework, integrating overlooked aspects such as energy, water and CO_2 emissions alongside design strategies.

Keywords Building circularity performance, Circularity measures, Circular economy evaluation, Micro-level circularity indicators, Carbon reduction, Life cycle assessment

Paper type Research article

1. Introduction

The linear economic model’s reliance on resource extraction and waste generations leads to severe socioeconomic and environmental risks, necessitating a shift to the circular economy (CE) (Franchetti and Apul, 2012; Goyal *et al.*, 2018; Horne *et al.*, 2023;

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Swarnakar and Khalfan, 2024). CE promotes a regenerative system replacing the "end-of-life" model with reducing, reusing, recycling and recovering materials (Kirchherr *et al.*, 2023; Bhavsar *et al.*, 2025). In buildings, circularity minimizes waste and optimizes resource usage through durable products made from secondary, non-toxic, sustainably sourced or renewable materials. It emphasizes space efficiency, flexibility and adaptability and prioritizes disassembly, reuse or recycling of materials, components and systems (WBCSD, 2022; Abad *et al.*, 2024).

Despite its potential, the practical application of CE in building design remains unclear (Gillott *et al.*, 2023), demanding measurable objectives, supported by indicators to enable clear evaluation (Ellen MacArthur and Granta, 2019). While CE is recognized and implemented in some countries, there is no agreement on how to measure the circularity of certain products and services (Harris *et al.*, 2021; Moraga *et al.*, 2019). Effective implementation requires a holistic classification of key performance indicators (KPIs) and a standardized assessment to measure progress and inform decision-making (Khadim *et al.*, 2023; Tokazhanov *et al.*, 2022). Assessing building circularity performance is crucial for integrating CE principles into buildings and reducing environmental impacts (Rahla *et al.*, 2019).

Mani *et al.* (2025) found significant inconsistencies in existing building circularity metrics, including variations in KPIs and calculation methods, underscoring a lack of standardization which is also highlighted by Khadim *et al.* (2022) and Kristensen and Mosgaard (2020). Deficiencies in existing metrics and KPIs include:

(1) *Inconsistencies across KPIs*: There is no standardized method for evaluating CE at the micro level (Khadim *et al.*, 2022; Kristensen and Mosgaard, 2020; Roos Lindgreen *et al.*, 2020). Khadim *et al.* (2022) discuss the lack of standardization specifically in building circularity metrics, highlighting how different studies have modified or developed new versions of KPIs and calculation methods. These variations in the incorporation of KPIs indicate a significant gap in adopting a holistic methodology with relevant KPIs (Norouzi *et al.*, 2021).

(2) *Emphasis on material flows*: The prevailing focus of the literature is on KPIs related to material flows, while other resources like energy and water, and emissions have received comparatively less attention or have been overlooked (Kristensen and Mosgaard, 2020; Zhang *et al.*, 2021).

(3) *Limited inclusion of circular design practices*: Many circular design practices have been neglected although few studies investigated some design-oriented KPIs such as adaptability and disassembly (Khadim *et al.*, 2022; Moreno *et al.*, 2016; Saidani *et al.*, 2019).

(4) *Neglect of key phases*: Current building circularity metrics overlook design, construction and assembly phases for buildings (Mani *et al.*, 2025).

(5) *Gaps in weighting approaches*: Weighting is rarely and inconsistently applied in current building circularity assessment methods. One Click LCA is notable for assigning higher weights to reuse, recycling and renewable content, and lower to downcycling, incineration and landfilling, offering more nuance than uniform metrics. However, it still fails to follow the 10 R hierarchy by treating renewable, reused and recycled materials equally, revealing a broader gap where weighting often overlooks CE priorities (Mani *et al.*, 2025).

These gaps highlight the need for identifying, validating and prioritizing KPIs for consistent and comprehensive building circularity assessment, enabling benchmarking and informed decision-making. To address these gaps, this study aims to develop the building circularity KPIs framework ($\mathrm{BC}_{\mathrm{KPI}}\mathrm{F}$). This study contributes to the theoretical domain by being one of the first to identify and prioritize critical circularity KPIs specific to buildings at all levels, providing a robust foundation for addressing the inconsistencies in building circularity assessments. The study is structured as follows: Section 2 reviews literature on micro-level KPIs; Section 3 outlines the research methodology for identifying, validating and prioritizing building-specific KPIs; Section 4 presents the study's findings, including the final KPIs list and their prioritizations; Section 5 discusses the findings and Section 6 concludes with recommendations for future research.

2. Building circularity assessment KPIs

CE operates at micro (individual products, companies and consumers), meso (eco-industrial parks) and the macro (cities, regions, nations) levels (Kirchherr *et al.*, 2017; Zhai, 2020). In the built environment, individual buildings are considered micro-level (Verberne, 2016). Consequently, this study focuses on KPIs related to micro level, specifically to building projects.

CE assessment refers to evaluating a building's transition toward CE by measuring adherence to CE principles and practices (Moraga *et al.*, 2019). Building circularity performance assessment examines how well building projects incorporate CE principles throughout their lifecycle (Corona *et al.*, 2019; Linder *et al.*, 2017), enhancing CE principles in design (Tokazhanov *et al.*, 2022). CE is operationalized through well-defined strategies and assessed using specific KPIs (Moraga *et al.*, 2019). Following Moraga *et al.* (2019), this study defines indicators or KPIs as variables providing circularity information, which can be quantitative or qualitative to measure circularity. KPIs are key for integrating CE principles into building designs and translating them into actionable plans (Moraga *et al.*, 2019; Tokazhanov *et al.*, 2022). KPIs are core elements of a circularity assessment, measuring aspects such as reused, recycled or bio-based materials quantities (Moraga *et al.*, 2019; Zhai, 2020).

Diverse methods, often combined, are employed to calculate circularity performance, with LC Life Cycle Assessment (LCA) being a prominent one, frequently combined with Material Flow Analysis (MFA), Material Flow Cost (MFC), input-output analysis and a set of KPIs (Lovrenčić Butković *et al.*, 2023; Roos Lindgreen *et al.*, 2020). CE assessment often employs a set of KPIs to measure circularity within a system (Koksharov *et al.*, 2019). Notably, the hybrid LCA approach, introduced by Genovese *et al.* (2017), which combines conventional LCA with CE KPIs, has been widely adopted. Studies by Lei *et al.* (2022) and Cottafava and Ritzen (2021) further apply this methodology to assess environmental impacts in CE evaluations. However, KPIs and LCA solely provide evaluations, which often involve multicriteria decision-making (MCDM) (Lovrenčić Butković *et al.*, 2023). dos Santos Gonçalves and Campos (2022) highlights the increased adoption of MCDM methods for evaluating circularity, requiring integration of various KPIs into composite indices.

Given the diverse definitions of CE (Parchomenko *et al.*, 2019) and challenges in metric selection (de Oliveira and Oliveira, 2023; Saidani *et al.*, 2019), standardized and comprehensive KPIs aligned with CE principles, 10 R strategies and design practices are crucial (de Oliveira and Oliveira, 2023; Moraga *et al.*, 2019). Standardized KPIs ensure a common language among stakeholders, preventing result misinterpretation (de Oliveira and Oliveira, 2023; Rahla *et al.*, 2019). To effectively assess circularity in buildings some requirements are essential. First, a systematic selection and categorization of KPIs is required. KPIs and their sub-indicators have been developed based on the specific circular practices and circular design practices (Mani *et al.*, 2025). As an example, “Dis- or re-assembly” KPI can serve as an indicator which can be facilitated through sub-indicators such as “Type of connections” and “Accessibility to connection” (Durmisevic, 2005). Therefore, to ensure a holistic view of circularity assessment, the KPIs should be considered across multiple dimensions including resource inflow (materials, energy and water usage), resource outflow (any non-recoverable resources including hazardous waste and emissions) and physical attributes (disassembly, adaptability, durability) (considering the definition adopted in this study and the study’s scope).

Furthermore, KPIs are mapped across the building’s lifecycle stages defined by the BS-ISO-EN-15978 (2011) standard: extraction/manufacturing (A1–A3), construction/assembly (A4–A5), use/operation (B1-B5), EOL stages (C1–C3) and phases beyond the system boundary (D). Existing metrics often overlook the extraction of material (A1), transportation (A2, A4, C2), operational energy (B6) and water usage (B7) phases (Khadim *et al.*, 2023). However, the inclusion of these stages is vital because they not only contribute significantly to emissions but also consume substantial amounts of energy and water (Nässén *et al.*, 2007). The use phase of buildings (B1–B5) is another resource-intensive stage, involving extensive energy, water and material usage, as well as emissions related to recycling, reuse and other processes (Crawford, 2011). Renewable energy supplies and water reusing or recirculation play a vital role in offsetting these resource demands during the operational phase (ISO 59020, 2023). However, at the EOL phase (C1–C3), 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), accompanied by water discharges into air, soil and water sources, as well as energy losses (ISO 59020, 2023). These processes collectively contribute to substantial emissions into the atmosphere (ISO 14044, 2006). Therefore, the inclusion of KPIs across all CE strategies and building phases is essential for an effective metric.

Many micro-level KPIs exist, such as the Linear Flow Index (LFI) for material linearity (Ellen MacArthur and Granta, 2019), disassembly KPI for evaluating disassembly potential (Durmisevic, 2005) and Flexibility (FLEX) for measuring flexibility/adaptability (Geraedts, 2016). However, they differ in scope, structure and methodological rigour. Variations in KPIs and methods exist across studies (Khadim *et al.*, 2022), while most focus on recycling and EOL management (Kristensen and Mosgaard, 2020). Gursel *et al.* (2023) highlight that micro-level circularity indicators remain underdeveloped, particularly for biobased systems, such as renewable resource use and cascading use. Design-related strategies such as modularity and adaptability which are crucial for extending building lifespans are also largely neglected (Kristensen and Mosgaard, 2020; Coenen *et al.*, 2021; Saidani *et al.*, 2019). Consequently, there remains a critical gap in identifying and consolidating circularity KPIs. The gaps identified in Section 1 further underscore the urgent need for a comprehensive and standardized approach to building circularity KPIs. This study addresses these gaps by developing the $\mathrm{BC_{KPI}F}$, which systematically identifies, validates and prioritizes critical KPIs tailored to building projects through a two-staged method involving a meta-synthesis of existing literature and a Fuzzy Delphi method, outlined in Section 3.

3. Research methods and design

The research aimed to systematically identify, validate and prioritize building circularity KPIs to assess building designs while integrating CE principles throughout a building’s lifecycle. Since numerous micro-level circularity indicators have been proposed across diverse industries, including packaging, manufacturing and construction, a structured two-stage method was employed to determine the most relevant ones for buildings, as outlined in Figure 1.

First, a systematic meta-synthesis reviewed literature across industries, ensuring inclusivity and a holistic approach to KPI identification. This process aimed to address the inconsistencies in existing metrics by systematically comparing and consolidating KPIs into a

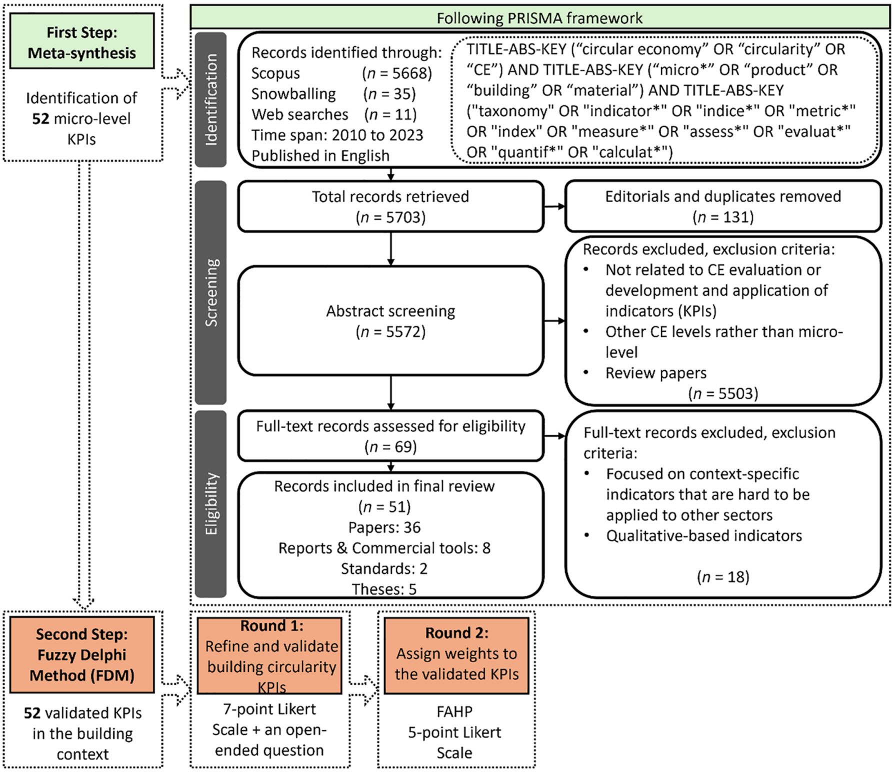


Figure 1. Research method and design. Source: Authors' own work

unified list. Then, a two-round Fuzzy Delphi Method (FDM) refined, contextualized and prioritized the identified KPIs for buildings. Expert feedback through FDM ensured KPIs were both theoretically robust and practically applicable. This section details the procedures and rationale behind each stage.

3.1 First step: meta-synthesis

A meta-synthesis of research papers, reports and commercial tools was conducted to comprehensively consolidate micro-level KPIs across various industries (material, product, building or construction projects and activities). The meta-synthesis process included choosing studies, combining interpretations and presenting the results (Hajiheydari and Dabaghkashani, 2011). The review process followed structured steps of Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (Page *et al.*, 2021) as described in Figure 1. The process included defining inclusion and exclusion criteria, creating a search string, searching across Scopus as the primary database because of its extensive inclusion of peer-reviewed documents (Chàfer *et al.*, 2021) and systematically screening articles. Additionally, snowballing method was used to identify additional sources (Badampudi *et al.*, 2015). Snowballing involves identifying additional papers by examining the references cited in a paper or the studies that have cited the paper (Wohlin, 2014). In addition to database searches, targeted web searches were conducted to identify relevant commercial circularity assessment tools used in practice, which were included where they reported measurable KPIs applicable to micro-level. A search string was created, testing different combinations of key terms related to "circular economy," "buildings" and "indicators," as shown in Figure 1. Studies were included if they developed or identified measurable micro-level KPIs, while sector-specific (e.g. municipal solid waste treatment plants and agricultural systems) (Rocchi *et al.*, 2021; Rondón Toro *et al.*, 2022) and qualitative-based indicators (Cayzer *et al.*, 2017; Flipsen *et al.*, 2016) were excluded, resulting in 51 relevant sources (Figure 1). Then, a bottom-up thematic analysis method categorized similar themes into KPIs (Braun and Clarke, 2006; Bowen *et al.*, 2012; Braun *et al.*, 2022), creating an initial list of KPIs as a basis for next step. The review primarily focused on identifying measurable KPIs from peer-reviewed sources and commercially developed circularity assessment tools. However, it is acknowledged that some industry tools, reports or broader grey literature sources may not have been fully captured, representing a limitation and an opportunity for future research.

3.2 Second step: Fuzzy Delphi Method

FDM was employed to refine, validate and prioritize building circularity KPIs by incorporating expert opinions while addressing uncertainty and subjectivity. Unlike traditional Delphi, FDM allows expert to express confidence judgments, enhancing results' reliability (Habibi *et al.*, 2015; Padilla-Rivera *et al.*, 2021). This is essential in navigating complexities and uncertainties in implementing circular thinking at the building level (Rahla *et al.*, 2021). Fuzzy Set Theory (FST) is particularly relevant for assessing building circularity, as standardized measurements are impractical due to unique building characteristics (Durmisevic, 2005; Van Vliet, 2018). As depicted in Figure 1, FDM was conducted through questionnaire surveys in two rounds which are discussed subsequently. The number of Delphi rounds was determined by the study's aim rather than a fixed iteration requirement. Prior research indicates that two to three rounds are sufficient for most Delphi studies, particularly when the expert panel is relatively homogeneous and the aim is to clarify or prioritize judgments. The study's objective is to refine and stabilize expert judgments regarding KPI relevance and importance, which requires fewer than three rounds, while additional rounds often yield limited gains and increase respondent fatigue (Skulmoski *et al.*, 2007; Hsu and Sandford, 2007; Hasson *et al.*, 2000).

3.2.1 First Fuzzy Delphi Method Round. The first FDM round aimed to validate and rank identified KPIs from the meta-synthesis approach.

Participant selection: This round was implemented with a panel of 17 experts from academia, industry and government. Ethics approval for conducting the survey was obtained from Deakin University, under approval number SEBE-2023–66, ensuring that all procedures complied with institutional and national guidelines for research involving human participants. Experts were selected based on their experience in circular economy, sustainable construction, waste management and building design. To ensure the relevance and representativeness of the panel, the Peer Esteem Snowballing Technique (PEST) was employed (Christopoulos, 2009). This method is particularly useful in expert-based studies where the target population is difficult to define, and where (1) the subject is too complex for general public responses and (2) the boundaries and size of the expert population are uncertain. These challenges applied directly to this research on CE KPIs in buildings. While PEST may raise concerns regarding selection bias, previous research shows that snowball-based approaches can converge toward representative samples when recruitment proceeds through multiple waves (Heckathorn, 2002). PEST reduces bias associated with initial selection by objectively identifying knowledgeable informants and validating expertise through peer nominations, rather than relying on reputation or position alone. As recruitment progresses, the influence of initial contacts diminishes, and an equilibrium composition of experts can be reached that is independent of the starting sample (Christopoulos, 2009).

The profiles of the selected experts are shown in Table 1. In typical Delphi studies, the panel size remains small (Lilja *et al.*, 2011). If participants are homogeneous, a sample size of

Table 1. Profile of the experts for FDM

Id	Group	Occupation	Experience	Description*	Country
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	Australia
P2″	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	Australia
P3″	Academic	University lecturer and researcher	>30 years	Expertise and active researcher in sustainable construction with extensive experience in life cycle assessment, circular economy applications and climate resilience in the built environment, including retrofitting existing and heritage buildings	UK
P4	Academic	University lecturer and researcher	11 years	Active researcher with expertise in circular economy, sustainable construction and modular building design, applying life cycle assessment and circularity metrics to reduce embodied impacts and improve resource efficiency in the built environment	Australia
P5″	Government	Policy researcher	11 years	Researcher specializing in circular economy strategies for the construction sector, with expertise in building product circularity, façade component material flows, demolition waste recycling and resource-efficient renovation systems	The Netherlands
P6	Industry	Circular economy specialist and consultant	7 years	Expertise in circular economy, life cycle assessment and strategies to minimize construction and demolition waste	Australia
P7″	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	Australia

(*continued*)

Table 1. Continued

Id	Group	Occupation	Experience	Description*	Country
P8″	Industry	Project manager	15 years	Experienced in both private and public sector, overseeing large-scale construction projects with expertise in circular economy, life cycle assessment and renovation strategies to decarbonize the built environment	Germany
P9	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	Australia
P10	Industry	CE project manager	6 years	Specializing in CE initiatives within the construction sector, with experience supporting the delivery of sustainability-focused projects in a large-scale national development company	Australia
P11″	Academic	University lecturer and researcher	10 years	Expertise in sustainable and circular building design, focusing on façade systems, energy efficiency and renovation strategies, as well as integrating product development and industrialized construction methods to decarbonize the built environment	The Netherlands
P12	Academic	University lecturer and researcher	11 years	Specializing in circular built environment, focusing on bio-based building products, circular product design and the integration of circularity principles into architectural education and practice	The Netherlands
P13″	Industry/ Academic	Architect/ University lecturer and researcher	16 years	Expertise in sustainable building design, material efficiency and circular economy principles. Experienced in reducing material demand, enabling design for deconstruction and reuse and collaborating with industry to minimize the built environment’s carbon impact	UK

(*continued*)

Table 1. Continued

Id	Group	Occupation	Experience	Description*	Country
P14	Academic	University lecturer and researcher	10 years	Active researcher in sustainable and circular built environment, focusing on life cycle assessment and the integration of CE principles in practice, leader and member of various international research-based institutions	Chile
P15″	Government	Policymaker	25 years	Senior sustainability professional in construction, design and materials management, contributing to national and international working groups on circular economy and responsible product procurement	Australia
P16″	Industry	Structural engineer	8 years	Delivering projects across research, education and commercial sectors, with specialist expertise in the application of design for manufacture and assembly principles	Germany
P17	Academic	University lecturer and researcher	12 years	Research leader in sustainable building innovation, with expertise in socio-technical transitions to low-carbon urban futures. Experienced in sustainable housing, compact city development and integrating circular economy principles across the building life cycle, with a strong focus on policy, regulation and industry collaboration	Australia

Note(s): ″Participant participated in both rounds
* The descriptions are slightly modified to maintain the anonymity
Source(s): Authors' own work

approximately 10–15 individuals may produce satisfactory outcomes (Skulmoski *et al.*, 2007). Studies employing similar methodologies to evaluate circularity in the construction industry or assess sustainability have used sample sizes 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). Although most experts were based in developed construction contexts, this reflects the study's focus on participants with both advanced knowledge and practical experience in circular economy implementation and circular building strategies.

Data collection instruments. The questionnaire used in this round comprised semi-structured questions. These questions were structured into six KPI categories – material, waste, energy, water, CO_2 emissions and design – with each category containing the relevant KPIs identified during the meta-synthesis. Experts then rated these KPIs using a seven-point Likert scale, from strongly disagree to strongly agree. Additionally, an additional open-ended question asked participants to suggest any additional KPIs. The survey was conducted online using the Qualtrics platform. Ethics approval for conducting the survey was obtained from the Deakin University, ensuring that all procedures complied with institutional and national guidelines for research involving human participants. On average, participants took about 25 min to complete the survey.

Data analysis. Data analysis in this round followed FST. Fuzzy logic translated the collected data into degrees of membership, capturing expert consensus and ensuring that indicators with higher agreement were included in the final KPI list. A threshold value ($\lambda = 0.65$) was applied to determine inclusion or exclusion of KPIs (Shen *et al.*, 2011), resulted in the "final list of KPIs" and their ranks (prioritizations) presented in Section 4.1. An open-ended question allowed additional KPI suggestions. Cronbach's alpha for the first questionnaire was 0.930, indicating high reliability (Kocak *et al.*, 2014).

3.2.2 Second Fuzzy Delphi Method Round. The second FDM round focused on assigning weights to the validated KPIs from the first FDM round.

Data collection. Recognizing that not all KPIs contribute equally to circularity, the weighting process is treated as a MCDM problem under uncertainty. In this context, methods such as the Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP) are commonly applied for variable weighting (Abdullah and Adawiyah, 2014; Öztürk and Batuk, 2007), particularly in CE assessments (dos Santos Gonçalves and Campos, 2022). ANP is typically employed when there are discernible interconnections among criteria and sub-criteria (Sánchez-Garrido *et al.*, 2022). Given the lack of evidence supporting such interdependence in this study (Lee *et al.*, 2021), AHP was deemed more appropriate for the objectives of the research. In a comprehensive systematic literature review by dos Santos Gonçalves and Campos (2022), AHP demonstrates the most commonly used method in the CE assessment area. The application of AHP is appropriate for this study, as the framework aims to prioritize KPIs and give them weights rather than to model detailed relationships between KPIs. Traditional AHP, which derives weights through pairwise comparisons, was enhanced with fuzzy logic (Buckley, 1985; Chang, 1996), which resulted in the Fuzzy AHP (FAHP) to better capture uncertainty and subjectivity in expert judgments (Kahraman, 2018; Lee, 2009).

Instruments and participants: The second-round questionnaire was designed based on the findings from the initial round. Ten participants from the first round (refer to Table 1) provided pairwise comparisons of the KPIs, employing a 5-point Likert scale, from equal to extremely important. The survey was conducted online through Qualtrics. On average, the completion time for the survey was approximately 35 min. Ethics approval for this round was covered under the same approval obtained for the first round (SEBE-2023–66), as it represented a continuation of the original study.

Data analysis: FAHP methodology was used to convert the collected linguistic assessments into fuzzy numbers and aggregated using geometric mean method. The fuzzy synthetic extent analysis method was then used to calculate the relative weights of the KPIs at their categories that reflect the relative importance of each KPI for the building circularity assessment, shown in Section 4.2. The derived weights are intended to support prioritize and compare circularity KPIs at the design stage. Their application in real-world building assessments requires additional assessment framework with mathematical formulations, which are beyond the scope of this study, and is identified as a direction for future research.

4. Findings

This section first presents the findings from the meta-synthesis and the first FDM round, followed by results of second FDM round. The results demonstrate both the comprehensiveness of the proposed $BC_{KPI}F$ and the prioritization of indicators across different building levels.

4.1 Circularity KPIs related to buildings

The meta-synthesis identified KPIs related to micro-level, categorized based on CE principles and 10 R strategies, serving as representations of these concepts (Muñoz *et al.*, 2023, 2024). CE principles – regenerate, slow the loop, close the loop and narrow – align with 10 R framework, which categorizes circular strategies into short (R0–R3), middle-long (R4–R6) and long loops (R7–R9) based on their impact (Bocken *et al.*, 2016; Çetin *et al.*, 2021; Kirchherr *et al.*, 2017; Mani *et al.*, 2025; Triguero *et al.*, 2022). Achieving CE objectives requires practices like design for durability, disassembly and resource efficiency (Minunno *et al.*, 2018; Shooshtarian *et al.*, 2023). To assess CE performance effectively, KPIs must translate these principles and strategies into measurable outcomes (Muñoz *et al.*, 2023, 2024). The meta-synthesis yielded 52 unique KPIs, which formed the basis for the first round of FDM. The degree of membership for each KPI was then calculated and compared against the Lambda value of 0.65. As shown in Figure 2, all KPIs surpassed this threshold and were included in the final list.

Based on the definition adopted in this study, the study's scope, and the requirements outlined in Section 2, KPIs covered resource inflow, resource outflow and physical attributes across design, construction, use and EOL phases of buildings. To align with ISO 59020 (2023) standard giving guidance on evaluating CE, KPIs were categorized based on its core circularity

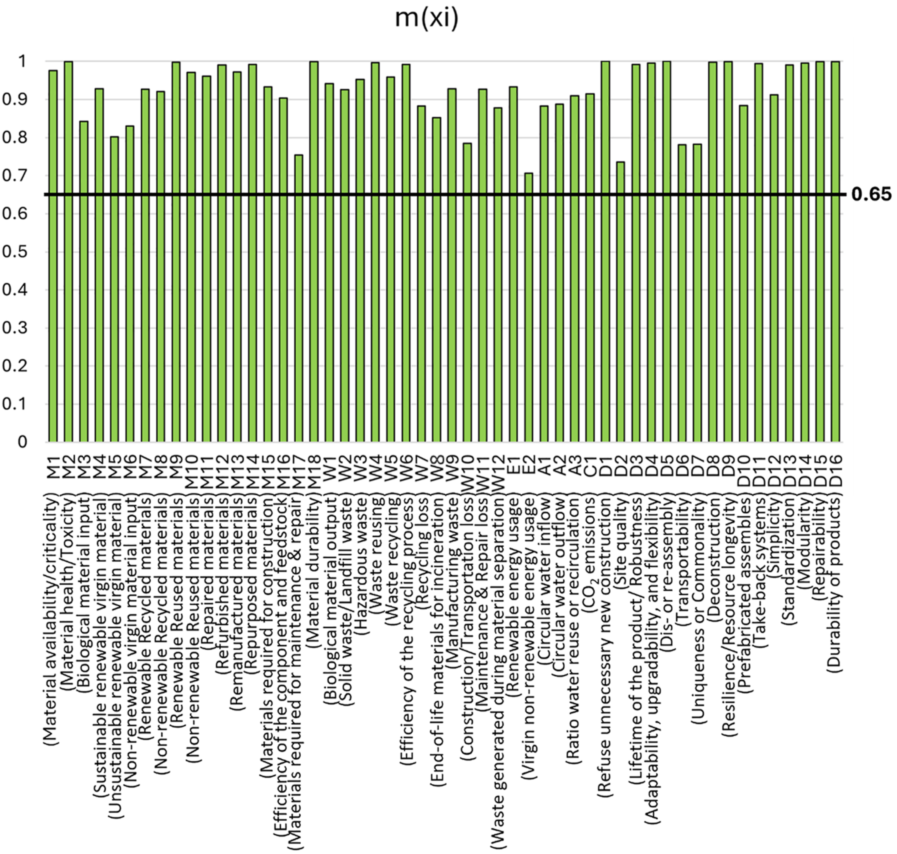


Figure 2. Degree of membership for each KPI compared to the threshold value (0.65). Source: Authors' own work

indicators: “Resource Inflows,” “Resource Outflows,” “Energy” and “Water.” The “Economic” category was excluded as it is beyond this study’s scope. While this standard allows for additional indicators and sustainability impact assessment methods, such as LCA, this study adds “CO_2 Emissions” as an additional category. Furthermore, ISO 20887 (2020) standard highlights “design for disassembly and adaptability” in sustainable construction, leading to the inclusion of an additional “Design and Others” category to ensure a comprehensive circularity assessment. The final categories are Material (M): 18 KPIs, Waste (W): 12 KPIs, Energy (E): 2 KPIs, Water (A): 3 KPIs, CO_2 Emissions (C): 1 KPI and Design and Others (D): 16 KPIs.

4.2 Building circularity KPIs framework

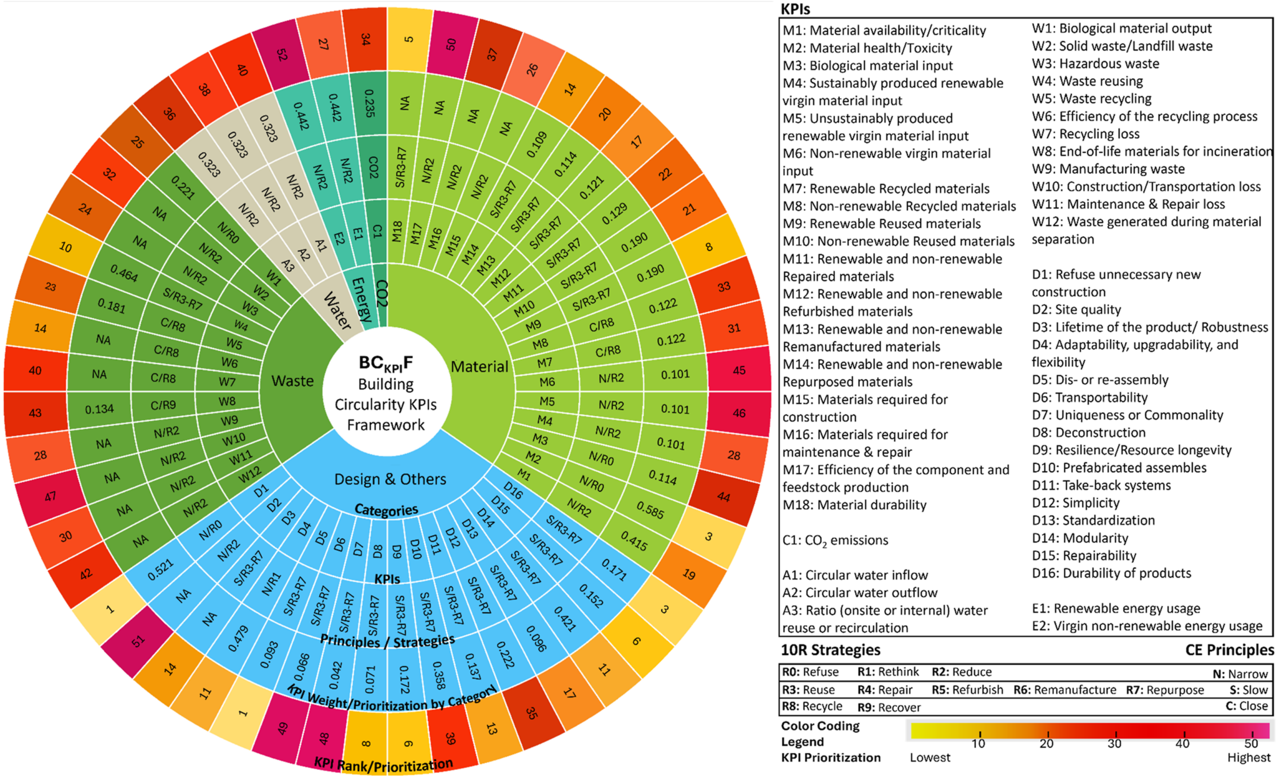
The FAHP process discussed in Section 3.2.2 was employed to calculate the global weights of KPIs at each category. These weights reflect the relative importance of KPIs in promoting circularity within its respective category. The prioritization of KPIs indicates the experts’ views on the most effective circular strategies in building design and lifecycle management. Based on the results, this study developed $BC_{KPI}F$, as illustrated in Figure 3. The innermost layer presents the KPIs categories, followed by the KPIs within each category. The subsequent layer shows the CE principles and 10 R strategies associated with each KPI. The next layer shows the relative weights of KPIs calculated at each category, while the outermost layer depicts KPI rankings based on the degree of membership (Figure 2).

Within the material category, reused materials received the highest weight, followed by repaired materials. Recycled and refurbished materials ranked closely behind, while renewable virgin materials received the lowest weighting. For waste category, waste reusing was prioritized highest, with bio decomposition and waste recycling ranking second and third, respectively. Energy recovery was considered the least preferred one. Among the KPIs related to the environmental performance categories including energy, water and CO_2 emissions, energy renewability was prioritized highest, followed by water circularity, and CO_2 emissions were ranked third.

Within the design category, the KPIs related to the building components, resilience and durability were ranked first and second, indicating strong emphasis on long-term performance. Repairability and take-back systems followed in third and fourth positions. Conversely, commonality and transportability were assigned lower importance, ranking eighth and ninth, respectively. Among the KPIs applicable to building system level, modularity received the highest ranking, reflecting its importance in flexible and circular building systems. Prefabrication was also highly valued, followed by simplicity in third place. Regarding the whole building design, refuse unnecessary new construction was prioritized over adaptability, underscoring the preference for minimizing new resource demand.

The findings regarding KPI ranks/prioritizations at all categories also highlight that “disassembly” (D5) and “refuse unnecessary new construction” (D1) achieved the highest rankings among the whole KPIs, both within the design category. These KPIs strongly promote the integration of CE principles such as slow and narrow principles and align with *R* strategies like reuse and refuse, respectively. The next eight top-ranked KPIs include durability of products (D16), material health (M2), material durability (M18), resilience (D9), repairability (D15), deconstruction (D8), reused material input (M9) and waste reusing (W4). Among these 10 highest-ranked KPIs, six belong to design category, three to material category and one to waste category.

Compared to previous frameworks, $BC_{KPI}F$ offers a more comprehensive and systemic approach to building circularity. By integrating major aspects of circularity, it enables a more informed selection of technologies, construction methods and materials for circular building designs. For instance, strategies such as deconstruction (D8) and prefabrication assemblies (D10) facilitate material recovery at EOL, while the use of biological materials (M3) and the avoidance of hazardous materials (M2) reduce environmental contamination. Although all



KPIs

M1: Material availability/criticality M2: Material health/Toxicity M3: Biological material input M4: Sustainably produced renewable virgin material input M5: Unsustainably produced renewable virgin material input M6: Non-renewable virgin material input M7: Renewable Recycled materials M8: Non-renewable Recycled materials M9: Renewable Reused materials M10: Non-renewable Reused materials M11: Renewable and non-renewable Repaired materials M12: Renewable and non-renewable Refurbished materials M13: Renewable and non-renewable Remanufactured materials M14: Renewable and non-renewable Repurposed materials M15: Materials required for construction M16: Materials required for maintenance & repair M17: Efficiency of the component and feedstock production M18: Material durability	W1: Biological material output W2: Solid waste/Landfill waste W3: Hazardous waste W4: Waste reusing W5: Waste recycling W6: Efficiency of the recycling process W7: Recycling loss W8: End-of-life materials for incineration W9: Manufacturing waste W10: Construction/Transportation loss W11: Maintenance & Repair loss W12: Waste generated during material separation
	D1: Refuse unnecessary new construction D2: Site quality D3: Lifetime of the product/ Robustness D4: Adaptability, upgradability, and flexibility D5: Dis- or re-assembly D6: Transportability D7: Uniqueness or Commonality D8: Deconstruction D9: Resilience/Resource longevity D10: Prefabricated assembles D11: Take-back systems D12: Simplicity D13: Standardization D14: Modularity D15: Repairability D16: Durability of products
C1: CO_2 emissions	
A1: Circular water inflow A2: Circular water outflow A3: Ratio (onsite or internal) water reuse or recirculation	E1: Renewable energy usage E2: Virgin non-renewable energy usage

10R Strategies **CE Principles**

R0: Refuse	**R1:** Rethink	**R2:** Reduce			**N:** Narrow
R3: Reuse	**R4:** Repair	**R5:** Refurbish	**R6:** Remanufacture	**R7:** Repurpose	**S:** Slow
R8: Recycle	**R9:** Recover				**C:** Close

Color Coding Legend KPI Prioritization

Lowest 10 20 30 40 50 Highest

Figure 3. Building circularity KPIs framework ($BC_{KPI}F$). Source: Authors' own work

KPIs are valuable and should be considered, their prioritization is essential for guiding decision-making and maximizing circularity outcomes in building designs. Moreover, the framework's alignment with international standards enhances its credibility and applicability across different regulatory and policy contexts.

5. Discussion

The $BC_{KPI}F$ offers a comprehensive, sector-specific and structured approach for selecting proper KPIs to assess building circularity compared to existing frameworks like Building circularity indicator (BCI), Whole building circularity indicator (WBCI) and One Click LCA. Previous metrics focus primarily on material flows, often neglecting crucial aspects like environmental impacts, energy renewability, water circularity and design strategies like simplicity and modularity. As a result, many existing approaches adopt narrow scopes (e.g. waste reduction or recycling rates), rather than a holistic view of circularity. In contrast, $BC_{KPI}F$ incorporates a broader range of CE strategies, covering resource inflows, outflows, energy, water, emissions and design attributes, ensuring a more detailed assessment. By integrating KPIs that span both technical and design-related dimensions, the framework supports circularity across multiple stages of building projects, from design decisions through construction, operation and EOL considerations. This framework enables different building stakeholders to engage with circularity using a shared assessment logic tailored to their roles and responsibilities.

While existing frameworks mainly focus on closing or slowing loops, through reuse and recycling, they often overlook higher-priority strategies such as R0-Refuse (Refuse Unnecessary Construction KPI) and R1-Rethink (Material availability/criticality KPI) which narrow the loop. By explicitly incorporating these strategies, $BC_{KPI}F$ addresses an important gap in current CE metrics. Even though many of the identified KPIs originate from existing frameworks, no single comprehensive metric covers all these crucial KPIs in an integrated method. As illustrated in Figure 3, each category targets specific CE principles and strategies. Material and waste KPIs focus on resource efficiency, reuse, reduction and recycling practices, which are critical for minimizing environmental impact and transitioning from linear to circular resource management. At the project initiation and design stages, KPIs related to refusing unnecessary new construction, material availability, modularity and standardization guide decisions that reduce resource demand before detailed planning. For architects and design teams, these KPIs provide early-stage guidance on embedding circular principles into building form, systems and material choices. During the construction and execution phase, material and waste-related KPIs support improved planning, monitoring and control of resource use, waste generation and recovery pathways, encouraging practices such as reuse of construction waste and minimization of material losses on site. For contractors and construction managers, the framework can be used to support procurement strategies and on-site practices that align delivery processes with circularity objectives.

Energy and water KPIs enhance circularity assessments by addressing resource conservation through KPIs such as renewable energy use and water recycling rates. These KPIs highlight opportunities to reduce dependency on finite resources and mitigate environmental degradation. Additionally, integrating CO_2 calculations strengthens the link between CE strategies and climate considerations, reinforcing the need to incorporate environmental performance into circularity assessment. This highlights the holistic nature of the proposed framework, as circularity scores alone are insufficient for informed choices (Niero and Kalbar, 2019). These elements are vital in supporting higher-level circular strategies, particularly *R*2 (Reduce) by minimizing energy and water consumption and lowering environmental impacts. For example, reusing water through closed-loop systems or utilizing renewable energy sources aligns with circular principles by reducing dependence on virgin resources. These environmental KPIs support decision-making at multiple stages. At the design stage, they guide early choices on efficiency and renewable resource integration.

During construction, they help reduce resource use and emissions. Additionally, in operation, they underpin long-term reductions in energy, water use and associated CO_2 emissions. Consideration of embodied emissions at EOL further reinforces the importance of early-stage design decisions in shaping environmental impacts. As circularity aims to move beyond waste reduction toward maintaining resources at their highest utility, integrating these overlooked dimensions and KPIs is essential for a more comprehensive assessment of circular performance in buildings.

A key distinction of $BC_{KPI}F$ is the inclusion of design-related KPIs, which have received less attention in previous CE metrics. Strategies like modularity, standardization and prefabrication underscore the importance of incorporating circular principles early in the design process to enhance reuse, refurbishment and recyclability of components and minimize waste (Minunno *et al.*, 2018; Machado and Morioka, 2021). Design KPIs form the backbone of circular building practices, ensuring structures can be reused or deconstructed without generating excessive waste. These design-oriented KPIs also play a critical role during the operational and EOL phases by enabling adaptability, ease of maintenance and component replacement, thereby extending building service life and reducing the need for demolition or major refurbishment. These KPIs reflect circular design practices that directly support higher-priority circular strategies, particularly R1 (Refuse), R2 (Reduce) and R3-R7 (Reuse, Repair, Refurbish, Remanufacture, Repurpose). These strategies are crucial because as we move toward the top of the 10 R framework, their impact on minimizing resource consumption and maximizing material retention becomes significant. Failing to incorporate these KPIs into assessments contributes to overlooking fundamental design-driven circularity aspects that enhance long-term resource efficiency and waste reduction. By linking these strategies to multiple project stages, from initiation and design to operation and EOL, the $BC_{KPI}F$ demonstrates its capacity to promote circularity across the entire building lifecycle.

Furthermore, our results show that reused and repaired materials received the highest weights, confirming the critical role of slowing loops rather than relying primarily on recycling. This is consistent with Muñoz *et al.* (2024) and Amarasinghe *et al.* (2024), who similarly emphasize reuse-oriented strategies. However, unlike their model, which excluded "refuse" from analysis, our framework demonstrates that "refuse unnecessary new construction" emerged as one of the most highly ranked KPIs. This distinction reveals the importance of avoiding resource demand altogether when circularity is assessed at the building scale. The lower prioritization of renewable virgin materials indicates a preference for conserving existing resources, reinforcing alignment with the 10 R hierarchy. It also reflects a clear preference for regenerative and value-preserving loops, indicating that preventing materials from entering waste streams is the most impactful strategy.

Moreover, energy renewability was prioritized over water circularity and CO_2 emissions, underlining the necessity to integrate renewable energy systems and reduce reliance on fossil fuels. The results suggest that while reducing emissions remains critical, experts might consider it as a result of implementing other CE and sustainability strategies rather than a primary factor to address on its own. For example, prioritizing Energy Renewability and Water Circularity directly reduces carbon emissions by decreasing reliance on fossil fuels and improving resource efficiency. Since these strategies inherently contribute to lowering emissions, experts may have ranked CO_2 emissions lower because it is already addressed through broader CE efforts rather than requiring separate intervention. Although its lower significance compared to energy renewability and water circularity, it still carries significance in circularity assessment. This aligns with Muñoz *et al.* (2024) and Khadim *et al.* (2025) where carbon performance was directly integrated as part of their circularity framework.

Additionally, the prioritization of design-related KPIs indicates that experts view design-driven interventions as the foundation of building circularity, placing higher value on strategies that enable adaptability, extend service life and facilitate reuse at EOL. These results align closely with the study by Amarasinghe *et al.* (2024), in which they highlighted modularity, prefabrication and disassembly as highly-ranked factors in material circularity assessment. Overall, experts prioritized strategies that conserve resources, extend lifespans and minimize the need for new material inputs. This outcome reflects a circular hierarchy consistent with the 10 R framework (e.g. Refuse > Rethink > Reduce > Reuse > Repair > Refurbish > Remanufacture > Repurpose > Recycle > Recover). These priorities align with recent literature that criticizes over-reliance on recycling and instead encourages systemic design and value preservation approaches (Muñoz *et al.*, 2024; Arup and Ellen MacArthur, 2022).

While $BC_{KPI}F$ provides a structured and comprehensive approach to prioritizing circularity KPIs, its applicability should be interpreted considering certain scope-related limitations. The exclusion of economic and social dimensions means that the framework primarily supports technical and environmental decision-making at the design stage and does not capture trade-offs related to cost, market readiness or social outcomes that influence real-world adoption. These limitations do not undermine the internal logic of the framework, but they indicate that $BC_{KPI}F$ is most appropriately applied as a decision-support and prioritization tool to measure the technical and environmental circularity of buildings. For policymakers and government agencies, the ranked KPIs provide an evidence-based foundation for shaping regulations, procurement requirements and incentive mechanisms that promote circular design strategies and discourage resource-intensive construction practices.

6. Conclusions

This study developed and validated the building circularity KPIs framework ($BC_{KPI}F$), which integrates a comprehensive set of weighted KPIs to systematically evaluate building circularity at the design stage. Unlike previous frameworks that addressed circularity in fragmented ways, $BC_{KPI}F$ systematically combines 52 KPIs within six main CE categories of material, waste, energy, water, emissions and design strategies, while embedding CE principles and 10 R strategies. The ranking and weighting of KPIs address existing inconsistencies, providing greater clarity on their relative importance and enabling more informed decision-making in building design and policy formulation. By shifting attention from isolated circular actions to a prioritized understanding of circularity, the framework encourages designers and decision-makers to reflect on where circular value is created, retained or lost across a building.

The originality of this research lies in its comprehensive coverage and prioritization of underrepresented CE aspects, particularly design-related strategies, such as refuse unnecessary new construction, modularity, prefabrication and standardization, which are largely overlooked in existing metrics. Although earlier frameworks primarily focused on Material and “Waste” categories, $BC_{KPI}F$ includes essential KPIs taken less attention or have been overlooked in previous studies, such as material health, biological material input and output, and material availability. In addition, the framework expands circularity assessment by incorporating “Energy,” “Water” and “CO_2 Emissions,” largely overlooked in existing frameworks. $BC_{KPI}F$’s prioritization of KPIs and their relative weights provides practical insights into the strategies most valued in practice. High-racked KPIs such as disassembly, refuse new construction, reused and repaired materials, material health, waste reusing and deconstruction reflect expert consensus on strategies that best align with high-level circularity principles.

In practice, $BC_{KPI}F$ equips industry practitioners with a structured guide to target and prioritize impactful interventions such as deconstruction, reuse of waste or selection of technologies, methods and materials with the highest circular impact. For policymakers, the ranked KPIs justify embedding circular design requirements such as modularity and reuse and discouraging excessive new development in procurement and regulatory frameworks and highlight the need to strengthen secondary material markets. Beyond these practice and policy implications, $BC_{KPI}F$ contributes directly to the United Nations Sustainable Development Goals (SDGs) by advancing responsible consumption and production (SDG 12), climate action (SDG 13), health and well-being through non-toxic materials (SDG 3), industry innovation and infrastructure (SDG 9) and sustainable cities and communities (SDG 11). Collectively, $BC_{KPI}F$ provides a basis for developing standardized circularity assessment tools that can facilitate benchmarking and decision-making across building projects. Future applications of the framework may include its integration into digital design workflows, circularity assessment tools or early-stage decision-support systems to compare alternative design scenarios based on their prioritization rankings.

Despite the comprehensive scope of the meta-synthesis, some relevant studies, industry reports or broader grey literature sources may not have been fully captured. More importantly, $BC_{KPI}F$ is conceptualized as a generalized framework designed to address a broader class of problems related to the lack of a comprehensive and standardized approach for evaluating building circularity at the design stage, rather than being limited to specific building cases or contexts. Generalization in this study refers to the ability of the framework to maintain conceptual validity and practical relevance across different building scenarios, types and contexts (Carvalho, 2012; Gregor and Jones, 2007). The generalizability of $BC_{KPI}F$ is supported by the abstraction of circular economy principles and 10 R strategies into a structured and weighted KPI set that is not tied to a specific building typology or geographic location, enabling its application across residential, commercial, institutional and other building types without compromising its underlying logic. The inclusion of expert input from diverse professional and contextual backgrounds further supports the applicability of $BC_{KPI}F$ across different contexts. While the KPIs have been identified from various studies, future research should explore the applicability of these KPIs across other industries to adapt these indicators to specific context of the industry. Additionally, the exclusion of other CE aspects, including economic and social factors, due to the study's scope represents another limitation that future research can further examine. Future studies may explore how economic feasibility, life-cycle costs, market readiness and social value considerations can be integrated alongside environmental and technical KPIs to support more holistic circularity assessments. Moreover, the dynamic nature of CE necessitates the need for continuous refinement of KPIs to incorporate emerging practices and technologies. This includes accounting for new construction methods, digital tools and circular business models that may influence circularity performance over time. Future application of $BC_{KPI}F$ in case studies is recommended which requires the development of mathematical formulations and scoring mechanisms. Therefore, future research should focus on refining building circularity assessment models and developing standardized metrics using $BC_{KPI}F$ to integrate comprehensive set of circular principles and strategies into the design stage. Collaboration among stakeholders is vital for the widespread adoption of CE practices in built environment.

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 disclosure

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

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