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Research Article

Assessing Circularity in Building Design: Testing the Building Circularity Performance (BCP) Model Through a Case Study

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Abstract
The transition toward a circular building sector requires robust assessment methods to measure circularity throughout the project lifecycle and compare design alternatives. However, existing circularity assessment methods lack a comprehensive systematic approach for building designs. In response, the Building Circularity Performance (BCP) assessment model is being developed based on established BCIs (Building Circularity Indicators) and ISO standards. This study tests the first version of BCP through a case study methodology, evaluating two design scenarios of a sample building-linear and circular-to assess the BCP's practicality in differentiating circularity levels. Results demonstrate that as the design transitions from linear to circular, the circularity score improves, highlighting the model's capability to quantify the impact of CE principles across different design strategies. The study also highlights potential pathways for adopting circular practices in building design. Unlike previous models, BCP incorporates a wider range of CE aspects, including material health, environmental impacts, renewable energy, water circularity, and broader design strategies like standardization, durability, and transportability. This framework would help decision-makers and designers to incorporate CE principles in projects, promoting a more circular building sector.

Received: 05/01/2025
Revised: 18/01/2026
Accepted: 21/01/2026
Published: 26/01/2026

Volume: 2026
Issue: 02
Pages: 56-65

Keywords: Building circularity assessment; Building environmental performance; Circularity adoption; Circular economy evaluation; Circularity indicators

Highlights
- BCP enables a comprehensive circularity assessment, guiding building circular design decisions.
- Design strategies and environmental impacts matter as much as reused or recycled content in circularity design.
- BCP addresses Key circularity assessment gaps by incorporating main circular economy aspects.

1 Introduction

The building sector is a major contributor to global resource consumption, waste generation, and carbon emissions (Ness & Xing, 2017; Oluleye et al., 2022). These impacts largely stem from the sector's prevailing linear economy ("take, make, dispose") (Gomis et al., 2022). In response, the circular economy (CE) has emerged as a sustainable alternative (Dalton et al., 2023) by promoting resource efficiency and waste reduction (Wu, 2022). A circular building minimizes waste and optimizes resource use throughout its entire life cycle by prioritizing adaptability, disassembly, and durable products made from secondary, non-toxic, sustainably sourced, or renewable materials, and enabling material reuse and recycle (WBCSD, 2022).

Transitioning to CE in buildings requires robust methods to evaluate or measure how well CE practices are integrated into building design (Corona et al., 2019; Linder et al., 2017). Circularity is typically assessed using Key Performance Indicators (KPIs) (Khadim et al., 2022), which are combined into circularity metric to measure CE implementation throughout a product's life cycle (Corona et al., 2019; Linder et al., 2017; Shevchenko et al., 2022). These KPIs provide a standardized framework for assessing circularity performance, facilitating information exchange and decision-making (Kirchherr et al., 2023; Saidani et al., 2019). Various building circularity assessment methods have been developed, including Material Circularity Indicator (MCI) (Ellen MacArthur & Granta, 2019), Building Circularity Indicator (BCI) (Verberne, 2016) and its subsequent improvements (Cottafava & Ritzen, 2021; Van Vliet, 2018), and the most recent version, Whole Building Circularity Indicator (WBCI) (Khadim et al., 2023). However, these methods they primarily focus on material flows while overlooking broader CE strategies and practices, such as modularity, reparability, and standardization, and environmental performance factors (Mani et al., 2025).

To address these gaps, this study presents the Building Circularity Performance (BCP) assessment model. Unlike previous methods, BCP integrates key design CE strategies such as repairability, transportability, commonality, and deconstruction potential, alongside environmental performance indicators, including CO_2 emissions, energy renewability, and water circularity. This paper applies the BCP model to two distinct building scenarios. The objective is to assess the effectiveness of BCP in quantifying circularity and supporting early design decision-making.

2 Methodology

The research uses the case study methodology to test the BCP assessment model on a building. BCP is a comprehensive building-focused circularity assessment model aligned with ISO 20887 (2020) and Bs Iso (2011); ISO 59020 (2023) standards. It builds upon previous methodologies, including Material Circularity Indicator (MCI) (Ellen MacArthur & Granta, 2019), BCI (Building circularity Indicator) (Verberne, 2016) and various iterations of BCI (Cottafava & Ritzen, 2021; Van Vliet, 2018) and the most recent comprehensive version, Whole Building Circularity Indicator (WBCI) (Khadim et al., 2023), along with other studies and tools developed across different industries (Akanbi et al., 2019; Linder et al., 2017; O'Grady et al., 2021; WBCSD, 2023). Grounded in the Bs Iso (2011); ISO 59020 (2023) and ISO 20887 (2020) standards and relevant literature (Anastasiades et al., 2023; Durmisevic, 2005; Geraedts, 2016; Khadim et al., 2023; Verberne, 2016), BCP assesses circularity at five levels of a building-material, element, component or product, system, and building. Additionally, it incorporates five out of six Brand layers (Brand, 1995): structure, skin, space plan, services, and site. The "stuff" layer (e.g., furniture) is excluded as it follows distinct circularity loops and life cycle processes (Khadim et al., 2022). BCP measures circularity of a building on a scale ranging from 0 (fully linear) to 1 (fully circular). KPIs were extracted from previous CE metrics through a meta-synthesis approach. These KPIs then were verified and assigned weights through a two-round Fuzzy Delphi method with industry and academic experts. However, the tested model in this study does not incorporate the relative weights. Figure 1 provides a detailed representation of the methodology steps.

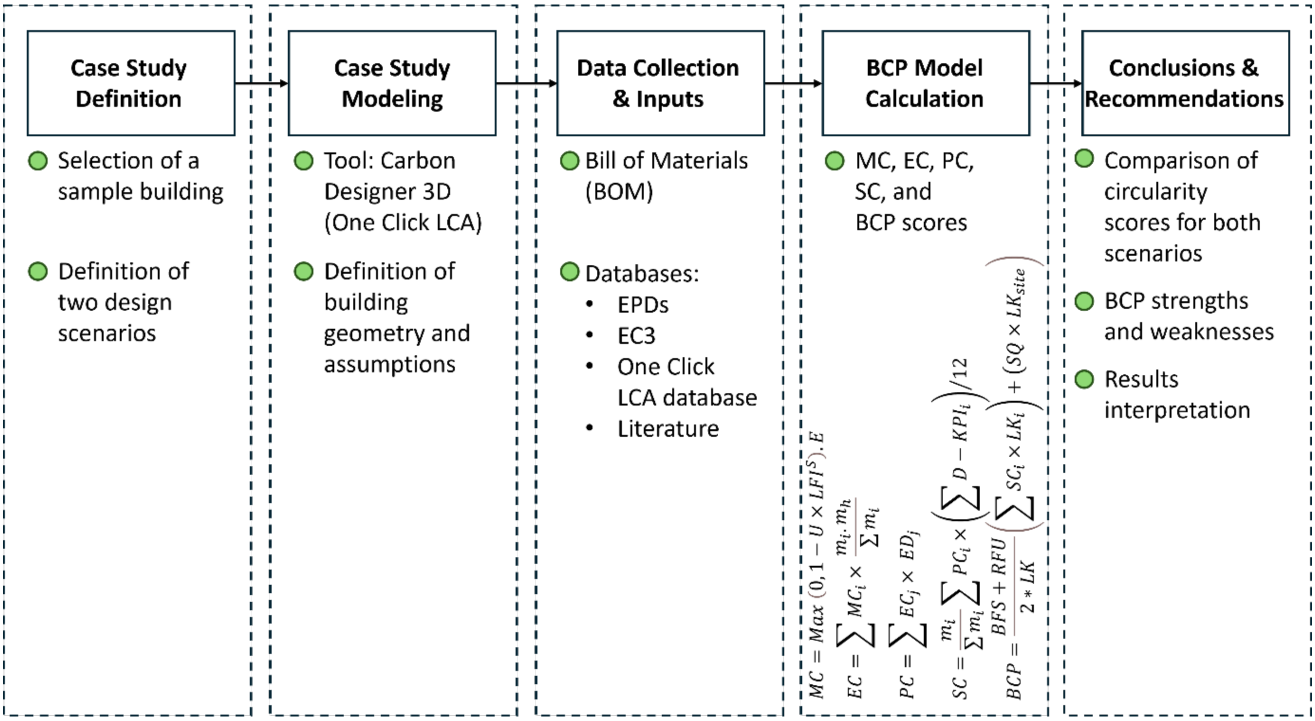

Figure 1: Research methodology stages.

2.1 How are green spaces and public parks perceived in Cairo

A typical sample building with two design scenarios, linear and circular, was defined. The sample building is assumed to be a single detached house located in Australia, with an expected lifespan of 50 years. Detailed descriptions of these scenarios and their differences are provided In Table 1. These scenarios were defined based on the verified KPIs incorporated in the BCP model and the scenarios defined in the study by Dams et al. (2021) and aligned with relevant CE policies and standards. Scenario 1 represents a sample building with conventional construction and no CE considerations, while scenario 2 is an example of a circular building with adaptive reuse and modular design following key CE design strategies and principles outlined by NSW Government of Australia (NSW Government, 2023) and relevant ISO standards (ISO 20887, 2020; ISO 59020, 2023).

Table 1: Case study scenarios - definitions and differences regarding key CE parameters.

Key CE Parameters	Scenario 1 (Linear)	Scenario 2 (Circular)
Construction method	Structure built onsite	Retrofitting/Reusing of an existing building structure
Materials sources	Raw materials/0% recycled (such as brick cladding, in-situ cast reinforced poured concrete frames, glass wool for insulation)	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	No modularity /No adaptability	Modular building system- prefabricated three-dimensional modules (e.g., wall panels, roof trusses) manufactured offsite and assembled onsite
	No disassembly	Using dry, mechanical connections for easy disassembly of components
	No take-back system	A comprehensive take-back system is in place for all components
Construction waste destination	Most materials are disposed of in landfills, steel is recycled	Materials are reused/recycled/remanufactured
Site condition	Built on a new/undeveloped site	Built on a previously occupied site

2.2 Case Study Modelling

The foundational building design for executing two scenarios was created using Carbon Designer 3D, a tool provided by One Click LCA. Detailed information on its geometry and assumptions are presented in the Appendices. The building's size and complexity were deliberately chosen to ensure the analyses remained manageable and straightforward while also allowing for meaningful scenario comparisons.

2.3 Data Collection and Inputs

Detailed Bill of Materials (BOM) for scenarios was obtained through the Carbon Designer 3D tool, consisting of 19 elements for scenario 1 and 11 elements for scenario 2, along with various materials. The required data including input/output materials scenarios, average lifespan, hazardous waste, total GWP, energy consumption, and hazardous content were gathered from multiple sources and databases, such as 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 & Huijbregts, 2019; Vieira et al., 2017). To support the evaluation process, data analysis was conducted within Excel datasheets.

2.4 BCP Model Calculations

The first step in calculating the BCP model is determining Material Circularity (MC), based on the Material Circularity Indicator (MCI) methodology (Ellen MacArthur & Granta, 2019), widely used in construction circularity assessments (Khadim et al., 2023). The Linear Flow Index (LFI) and Utility (U) are key components, with some modifications for criticality (S) and environmental performance (E) indicators (Equation 1).

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

Materials classified as critical natural capital should be minimized. The Criticality Indicator (S) is adapted from Vieira et al. (2017) and integrated into LFI (Anastasiades et al., 2023), where rare materials decrease MC by increasing LFI. BCP also incorporates Environmental Performances Indicator (E) into MC, including Global Warming Potential (GWP) (E'), renewable energy consumption (EN), and water circularity (W) similar to MDI by Mesa et al. (2020). Calculations for U, LFI, and E and their corresponding formulas are outlined in Appendix.

Secondly, Element Circularity (EC) is calculated for each building element by normalizing the sum of MCs for all materials in an element, weighted by their mass (mi), while BCP improves circularity assessment by integrating a Hazardous Content indicator (mh) based on the D-DAS method (Akanbi et al., 2019) (Equation 2), flagging elements with over 0.1% SVHC (List of Substances of Very Hight Concern) under EU REACH Regulation (Klaschka, 2017).

$$EC = \sum MC_i \times \frac{m_i.m_h}{\sum m_i} \tag{2}$$

Next step is to calculate the Circularity of Product level (PC) for each product. PC is calculated by normalizing the sum of ECs for all elements in a product, incorporating an Element Disassembly (ED) indicator based on Durmisevic (2005) to reflect disassembly ease (Equation 3).

$$PC = \sum EC_j \times ED_j \tag{3}$$

Next step is calculating System level Circularity (SC), where BCP focuses on four "Shearing Layers"—Structure, Skin, Services, and Space Plan. While WBCI incorporates element disassembly indicator at this level, BCP determines SC by normalizing the sum of Product Circularities (PCs) across products in a system, incorporating key circularity indicators, including Product Disassembly (PD) (Durmisevic, 2005), Deconstruction (DE) (O'Grady et al., 2021), Resilience/Longevity (Re) (O'Grady et al., 2021), Durability (D) (Mesa et al., 2020), Transportability (T) (Coenen et al., 2021), Standardisation (N) (Mesa & González-Quiroga, 2023), Commonality (C)) (Mesa & González-Quiroga, 2023), Repairability (RP) (Ruiz-

Pastor & Mesa, 2023), and the existence of Take-back systems (TB) (Struck & Flamme, 2023) for each product and using product mass as a normalization factor (Equation 4).

$$SC = \frac{m_i}{\sum m_i} \sum PC_i \times (PD_i + DE_i + Re_i + N_i + C_i + T_i + RP_i + D_i + TB_i)/9 \quad (4)$$

BCP or the circularity performance of the whole building level is determined by normalizing system circularity scores (SCs) using multiple key indicators instead of mass. WBCI integrates building Level of Importance (LK) (Verberne, 2016) and Flexibility Scores (BFS) (Geraedts, 2016) instead of the mass (kg) of the system. However, BCP improves it by incorporating two key indicators of Refusing Unnecessary Construction (RFU) (Arup & Ellen MacArthur, 2022) and Site Quality (SQ) (Fagone et al., 2023), Modularity (M), Simplicity (S), and Prefabricated Assemblies (FB) (Mesa & González-Quiroga, 2023) as outlined in Equation 5.

$$BCP = \frac{BFS + RFU}{2 \times LK} \left(\sum SC_i \times LK_i \times \frac{M_i + S_i + FB_i}{3} + \frac{SQ}{5} \times LK_{site} \right) \quad (5)$$

Here, LKi refers to the LK value for the ith system, covering the structure, skin, services, and space plan while excluding the site since it is integrated into the SQ.

3 Results and Discussion

This section analyses circularity outcomes for scenarios across different levels: MC, EC, PC, SC, and BCP. The results highlight the effectiveness of various design strategies in enhancing circularity performance.

3.1 Material Circularity (MC)

This level is primarily influenced by the proportion of recycled, renewable, reused, and bio-based materials. Scenario 1 relies heavily on virgin resources, resulting in a low average MC score, as shown in Figure 2. Scenario 2, which prioritizes reclaimed and remanufactured materials, achieves a higher average MC score, demonstrating the effectiveness of material reuse in circularity performance. Environmental performance is another aspect that significantly impacts MC. Incorporating this indicator in the calculation is crucial, as neglecting it can significantly lead to an overestimation of the circularity scores. Figure 2 compares MC scores with and without E indicator. For scenario 1, the average MC drops significantly when E is considered-a nearly threefold difference, an indicator overlooked in previous BCIs. A similar downward trend is observed in scenario 2, though the extent of the drop varies.

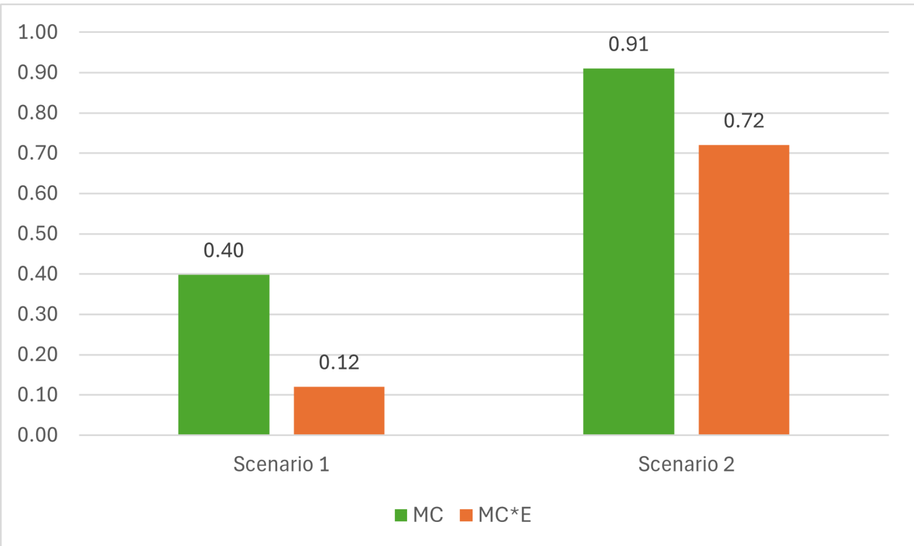

Figure 2: Comparison of MC with and without E indicator.

3.2 Element Circularity (EC)

At the element level, structural, façade, finishing, and other building elements are assessed. Elements composed of materials with higher MC scores and non-hazardous content tend to perform better. For instance, renewable material-based elements, such as cork floor tiles in scenario 2, achieve a higher circularity score than nylon carpet tiles in scenario 1 (Figure 3). For wall façade elements, the prefabricated timber cladding wall assembly in scenario 4 has a higher EC than brick cladding elements in scenario 1. These results demonstrate that BCP can support element selection at the design stage by comparing the circularity performance of different elements.

3.3 Product Circularity (PC)

At the product level, the disassembly potential of elements is considered. Products or components made of easily disassembled elements achieve higher PC scores. Figure 3 compares PC scores for the same examples analyzed at the element level, highlighting the impact of the disassembly indicator on circularity performance. In this example, while the EC score of a bio-based element like timber wall assembly in scenario 2 is high (0.81), its PC score is lower (0.7) due to limited disassembly potential. The same applies to cork floor tiles, another bio-based element. This underscores that material origin, though significant, does not guarantee high circularity if disassembly is not feasible at the end-of-life.

3.4 Element Circularity (EC)

System-level circularity is influenced by KPIs such as deconstruction, transportability, and repairability of all products/components in a building system. In scenario 1, the skin layer exhibits the highest circularity compared to the space plan and structure. This is mainly due to the traditional concrete structure, which has low deconstruction and repairability scores and lacks standardization. Scenario 2 further enhances circularity through modular design, leading to an equal SC score for span plan skin layers. This modular approach improves disassembly, resilience, transportability, and other strategies across all layers. SC scores for both scenarios are shown in Figure 3.

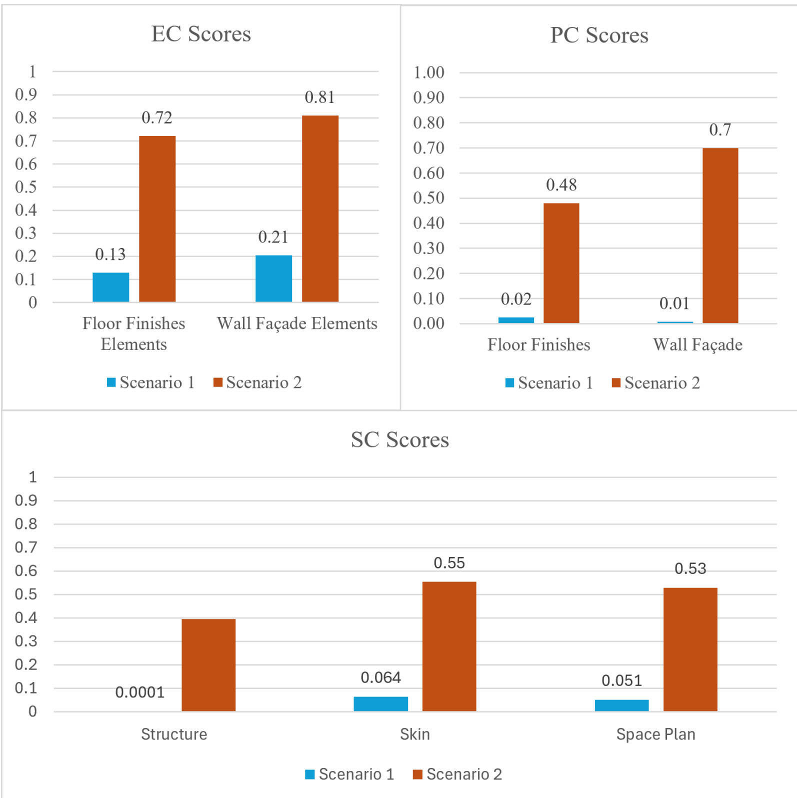

Figure 3: EC, PC, and SC scores for various building elements/components/layers across two scenarios.

3.5 Building Circularity (BCP)

The overall building circularity performance (BCP) reflects the combined impact of material, element, product, and system circularity by considering the adaptability potential of the building and the reused area. BCP also considers the quality score for the site layer. Figure 4 illustrates the circularity scores for each scenario. As expected, scenario 1 (linear) demonstrates a very low circularity score. Scenario 2, designed for maximum adaptability and reuse, achieves a higher circularity score, emphasizing the role of modular, remanufactured, and bio-based materials to attain high circularity performance.

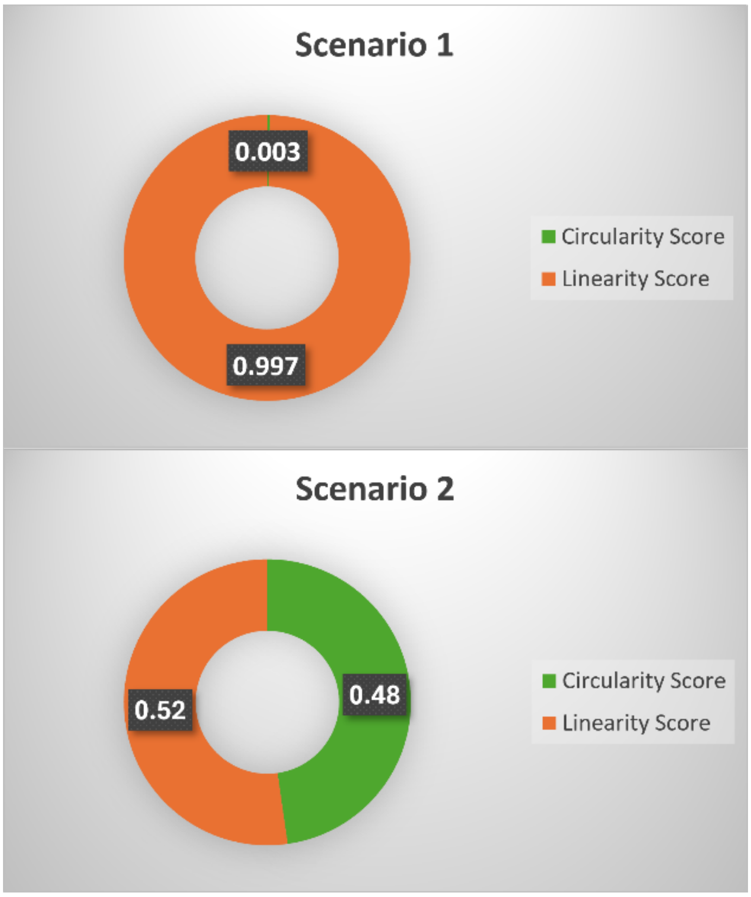

Figure 4: BCP scores for two scenarios.

The findings highlight the effectiveness of various CE strategies in building design and demonstrate the BCP's applicability in evaluating circularity performance across different levels. Unlike existing methods that focus mainly on materials inputs and outputs, BCP integrates broader CE strategies such as repairability, standardization, transportability and adaptability alongside environmental indicators such as CO_2 emissions, energy renewability, and water circularity, which are largely overlooked. Results indicate that while material selection is important, circularity performance is significantly influenced by design-related CE strategies, such as deconstruction and disassembly potential of components and their commonality and standardization. BCP's ability to capture these factors supports early design decision-making, allowing designers to compare alternative solutions and select the most circular options. For effective circular building design, decision-makers should not only focus on the reused or recycled content of materials but also consider the materials' carbon footprint, renewable energy consumption, and water circularity. They must also prioritize modularity, prefabrication, and standardization to enhance disassembly, adaptability, and reusability of components, ensuring a more circular building design.

4 Conclusions

This study applied the BCP assessment model to evaluate and compare two building design scenarios, linear and circular. The findings reinforce BCP's applicability in quantifying circularity at multiple levels, from materials to whole buildings, incorporating key factors such as material criticality, environmental performance, disassembly potential, and waste minimization. Unlike previous models, BCP expands the scope of KPIs beyond material flows to include environmental performance and various design strategies like durability, standardization, and transportability. This comprehensive approach ensures a balanced and realistic evaluation of circularity at the design stage, ensuring a more holistic and realistic circularity assessment at the design stage. By testing BCP through a case study, this research contributes to the ongoing development of CE assessment methodologies in the building sector, supporting architects, engineers, and policymakers in making informed circular design decisions. One limitation of this model is that it does not yet consider the varying significance of KPIs or their relative weights, which may affect decision-making. Future research will refine the model by incorporating relative weights for KPIs and expanding scenario testing to enhance its robustness and practical application.

Funding

N/A

Ethical Approval Declaration

The study was conducted in accordance with established standards for research integrity and ethics.

Data Availability Statement

All data supporting findings are available from the authors upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendices

Table A: 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) (m2)	300 m2	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 m2
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

Table B: BCP calculations and formulas details.

KPI	Formula	Sub-indicators
E (environmental performance)	$E = \frac{E' + EN + W}{3}$	GWP total; renewable energy; Water circularity
E' (GWP total)	$E' = 1 - \frac{C}{C_{max}}$	GWP pf the case study; maximum GWP within the material category
U (material longevity)	$U = \frac{0.9}{\min(FL, TL)/L_{brand}}$	Technical lifetime; Functional lifetime
LFI (material linearity)	$LFI = \frac{V_{nr} + W}{2M'}$	Virgin input; Total mass; Waste
M' (total mass)	$M' = M + M_{cl} + M_{rm} + M_{rpl}$	Mass of material; construction; repair and maintenance; complete replacement
Vnr (virgin input)	$V_{nr} = M' (1 - V_r - F_r - F_{u} \cdot - F_{rep} - F_{fb} - F_{mu} - F_{pr} - F_b)$	Virgin; Reused; Recycled; Bio-based; Non-Renewable virgin; Renewable virgin; Repaired; Refurbished; Remanufactured; Repurposed
W (total waste)	$W = W_O + W_C + W_{cl} + W_{rm} + W_{mn} + W_{ms} + W_H$	Unrecoverable; Recycling; Construction; Maintenance and repairs; Manufacturing loss; Material separation; Hazardous

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