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Circularity-based embodied carbon performance in building design: Index development and circular initiatives

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ABSTRACT

This study introduces the Circularity-based Embodied Carbon (CiBEC) index, a comparative metric designed to assess the effects of circular actions on the embodied carbon (EC) of building projects. Built upon the conventional EC measurement, this index enhances traditional approaches by incorporating inclusive material inflow and outflow allocations, acknowledging variations in usage intensity, and factoring in potential changes to building lifespan strategies. Unlike conventional methods, it also recognises the collective efforts of all stakeholders - including third-party contributors - by fairly redistributing carbon savings across product (A) and beyond the building (D) phases of the life cycle assessment, offering a more holistic and equitable perspective. While demonstrated on a global scale, the index is applied to a real office building project to validate its practicality and demonstrate real-world applicability. Both individual and combined circular scenarios are assessed, revealing how key benefits from circular initiatives - often unaccounted for in conventional methods - are effectively captured through the CiBEC framework. The results indicate that among the eight developed circular scenarios, two - specifically, renovation and the multi-use of building spaces - are identified as EC-intensive. In contrast, the remaining scenarios achieve reductions of up to only 10 % when the conventional approach is used. However, when assessed using the CiBEC method, the “renovation” scenario notably demonstrates a 36 % reduction. Furthermore, the study shows that integrating various circular strategies through the development of seven combined scenarios can lead to substantial EC reductions, decreasing the initial EC from 629 to 191 $kgCO_2$ eq./m^2. This significant reduction is not achieved through a simple statistical aggregation but through the complex interactions among the different strategies. Therefore, it seems that while the CiBEC index is most effective during the early design stages, it also allows project stakeholders to refine and monitor EC reduction throughout the project’s lifecycle.

1. Introduction

The building industry bears a considerable responsibility in global greenhouse gas (GHG) emissions, accounting for 40 % (World Green Building Council, 2019). Of this, one-third of emissions stems only from embodied carbon (EC), encompassing GHG in the entire building life cycle, ranging from extracting material and component productions, transportation, construction methods, and maintenance, to end-of-life (EoL) and demolishing (Grazieschi et al., 2021). These contribute significantly to environmental degradation, climate change, and resource depletion (Chastas et al., 2018; Girotto et al., 2023) mainly because the manufacturing of building materials, including cement, steel, and glass (Omar et al., 2014), as well as activities such as construction and demolition, typically entail energy-intensive processes that release substantial amounts of CO_2 (Cabeza et al., 2021).

As buildings become more energy-efficient and the electricity grid shifts towards local and low-carbon energy sources, operational carbon emissions are anticipated to decrease, emphasising the increasing importance of EC (Hafez et al., 2023; Hu, 2023). The EC share in new buildings typically ranges from 20 % to 50 %, though in some cases it can exceed 90 % (Chastas et al., 2018). This shift marks a significant transition from prioritising operational carbon to EC, which is poised to

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become the dominant source of emissions in the building sector (Ahmadi et al., 2024).

The growing trend of reducing EC in building sector, underscores the need for implementing and testing a variety of sustainable practices (Andersen et al., 2020; Myint and Shafique, 2024) through research, policy, design, and technology (Craft et al., 2024), with a particular focus on incorporating circular economy (CE) principles. The CE can reduce EC at various stages of a resource's life cycle by applying 'narrow resource loop' principles during the initial phases, minimising EC at the end of life through 'close resource loop' strategies, and lowering EC during the operational phase by extending resource lifespans with 'slow resource loop' principles (Ellen Macarthur Foundation, 2021). One prominent framework called the 10R framework (Bocken et al., 2016; Konietzko et al., 2020; Muñoz et al., 2023) defines three classes of resource loops: (1) narrow loops (R0-R3), aimed at reducing material use by eliminating unnecessary materials; (2) slow loops (R3-R6), focused on extending product lifespans by reusing materials in their original function; and (3) closed loops (R7-R9), which repurpose materials for new uses. However, there is a research gap in quantifying the real-world potential of circular activities to reduce EC. This lack of clarity leaves decision-makers without clear guidance on which practices have the greatest impact on emissions reduction, particularly in the early project stages (Densley Tingley et al., 2018).

Life Cycle Assessment (LCA) is a quantitative method used to assess the environmental impacts of products and services. It is applied widely for assessing the EC in building sector using the functional unit of kg CO_2 eq./m^2 (Dixit, 2017). Over the years, several LCA methodologies have been developed, with the European standards EN15978 and EN15804 being the most widely recognised, particularly in the built environment (Mirzaie et al., 2020). EN15978 is frequently employed to assess environmental impacts across a building's entire life cycle, encompassing the product stage (modules A1–A3), construction process stage (modules A4–A5), use stage (modules B1–B7), end-of-life stage (modules C1–C4), and benefits beyond the life (module D) (Q4 addressed). EN15804 is used for creating environmental product declarations (EPDs), which quantify the environmental impact of building materials based on specific performance indicators (BSI, 2019). In parallel, the European Commission developed the Product Environmental Footprint (PEF) method to harmonise LCA practices across diverse sectors (Manfredi et al., 2012). While not yet fully integrated into building-specific standards, PEF promotes consistent and comparable environmental assessments, particularly for products, by including guidance on impact categories and allocation rules for recycled content, supporting greater alignment with circular economy objectives (Pedersen and Remmen, 2022).

Despite the widespread recognition of these European-based methods by researchers or official mechanisms, including standards, regulations, and rating systems, challenges persist in the inconsistent applications used for comparing and tracking EC reduction (Ahmadi et al., 2024). These inconsistencies are largely due to variations in system boundaries, an issue that becomes especially pronounced when circular actions shift the predefined LCA boundaries (Decorte et al., 2023; Illankoon et al., 2023). One particular challenge that researchers have encountered stems from the diverse methods used to allocate EC reduction, or "saved carbon" across systems (Mirzaie et al., 2020). These varying allocation approaches often lead to the separate reporting of saved carbon beyond the building's life cycle (i.e., phase D that can also be extended for phase A of other projects), where it is documented as distinct credits (Arenas and Shafique, 2024), but excluded from the total EC calculation (Temizel-Sekeryan et al., 2023). A particular difficulty lies in how to account for the contribution of circular actions—such as incorporating recovered materials within a project or processing materials at the project's end-of-life (EoL) for reuse in other projects -in the overall saved carbon (Seyedabadi et al., 2023). In this regard, some researchers allocate the EC reduction to individual project only (Lei et al., 2023). For instance, if a construction project incorporates recycled steel, the resulting EC reduction is assigned solely to that project (Keena et al., 2023). However, an alternative perspective exists - one that considers the broader impact. In this view, the reduction is distributed across multiple projects using a weighting scale. This approach acknowledges that circular actions can have ripple effects beyond a single project boundary (Blay-Armah et al., 2024).

Beyond allocation, the complexities of extending a project's lifespan, as a system boundary, introduce additional challenges to the EC measurement process (Joensuu et al., 2022). Consider a building designed for a specified life span beyond the initial construction phase. Such projects raise critical questions regarding how to account for the environmental impact of a building when its lifespan is extended through renovation or refurbishment, particularly by reusing elements like the foundation and structure (Forsythe and Wilkinson, 2015). This aspect of circularity -where materials gain a new or extended life beyond their original context-introduces unique challenges that contribute to variations in LCA outcomes (Luo, 2022; Nawarathna et al., 2021). Hasik et al. (2019) proposed an LCA framework for comparing refurbishment scenarios of an existing building with those of new construction. In this framework, the LCA boundaries were defined to facilitate comparisons between new construction and renovation projects, while excluding the existing building. Similarly, Decorte et al. (2023) compared LCAs for new construction versus renovation, highlighting the importance of distinguishing between buildings from different construction periods within the reference system period. However, a key critique of this approach is that, in circular actions, we are not dealing with entirely separate systems. Instead, we are working within a single system that experiences inputs (inflows) and outputs (outflows) under new conditions, such as an extended life cycle, rather than creating an entirely new system.

Another notable challenge in current measurement approaches is the insufficient consideration of usage intensity. For instance, a commercial office building operating double shifts can accommodate more people or companies outside standard working hours (Ellen MacArthur Foundation and Arup, 2024). This increased utilisation reduces the need for additional buildings, thereby lowering the overall EC. Similarly, when multiple companies share a building through innovative approaches like hot-desking (Arup, 2016), it further minimises the demand for new construction by maximising the efficient use of existing space. However, reductions in carbon emissions resulting from changes in usage intensity are often overlooked in LCA assessments, which typically focus on predetermined service functionalities. Accurately capturing this reduction becomes particularly challenging when circular actions, such as changes in functional services or study periods, alter the specified LCA boundaries (Lu et al., 2024). Another complication is that usage intensity lacks a standardised unit of measurement - it may be considered in terms of hours of use, number of occupants, or number of operating businesses (Ellen MacArthur Foundation, 2015). As such, it cannot be directly integrated into the EC functional unit and should instead be treated as a qualitative factor influencing the overall environmental impact.

Hence, there is a clear and pressing need to develop a comparative index for evaluating the impacts of circular actions through the lens of EC. Such an index should build upon existing LCA methodologies while integrating key circularity factors - such as material inflows and outflows, extended building lifespans, and usage intensity patterns - all of which may influence the definition of LCA boundaries. Moreover, it is essential that all circular actions be quantified in terms of their contribution to embodied carbon, and that the efforts of all stakeholders, including third parties, are equitably recognised. This can be achieved through a transparent distribution of both increases and reductions in EC across the project lifecycle. To address this gap, the present study introduces a circular-based EC index (CiBEC). The CiBEC applicability is demonstrated by comparing various circular scenarios against the baseline design of a real case study, referred to as the BaU project, using both conventional EC measurement and CiBEC.

2. Method and materials

CiBEC is developed based on the leading LCA method, EN 15978, to measure EC reduction resulting from circular actions through a comparative analysis between business-as-usual (BaU) designs and new circular initiative designs. The objective is to assess and incorporate factors influencing circularity that are not adequately reflected in conventional EC measurement, including inflow, outflow, lifespan, and usage intensity (Ellen MacArthur Foundation, 2015), impact EC reduction through circular strategies. A cradle to grave EC is typically determined using Equation (1), hereafter called as $EC_{Conventional}$ in line with reference of BS EN 15978 (Q4 addressed), which involves calculating the EC of all materials and services used in a project's life span. This calculation for cradle to grave LCA covers different stages including product (phase A1-A3), construction (phase A4-A5), use (phase B), and EoL (phase C).

$$EC_{Conventional} = \sum_{Material/Activity} \left(EC_{Product} + EC_{Construction} + EC_{Opertional\ Use} + EC_{EoL}\right)$$

Equation (1)

The development of the CiBEC index, as shown in Fig. 1, involves two levels of application: (1) building materials level and (2) whole building level. At the building materials level, the CiBEC accounts for material inflow, outflow, and products' lifespan, while at the whole building level, it considers whole building's lifespan and usage intensity. When discussing material inflow, it can include a mixture of virgin inflows as well as circular inflows including reused, recycled, and bio-based material (Kiessé et al., 2017). For instance, concrete made of aggregate extracted completely from quarries is all virgin, while concrete whose aggregates are supplied from crashed downcycled concrete from previous projects has circular inflows. Similarly, material outflow can be originated from a wide range of actions, including complete landfilling, full reuse, recycling/downcycling of products and materials, and energy recovery (Marsh et al., 2022).

2.1. Components of proposed circular-based embodied carbon index

The CiBEC index, as illustrated by Equation (2), comprises three components (1) net Measured EC (EC_N) aligning with contemporary practices. EC_N encompasses a broader spectrum of efforts, ranging from stakeholder engagement to the integration of circular economy principles as intrinsic value-driven actions within the project framework; (2) impact of the whole project lifespan (F_L). F_L quantifies the environmental implications associated with the duration of the project's existence, acknowledging that longer lifespans may entail both reduced resource consumption and extended environmental benefits; (3) impact of the whole building usage intensity (F_U), primarily impacts through controlling occupancy rates, operational hours, and activity levels. Higher usage intensity can lead to increased resource consumption, such as energy and water, but it can also optimise the efficiency of utilisation in the building's infrastructure and potentially reduce the need for constructing additional buildings. By incorporating F_U and F_L, the CiBEC index integrates the temporal dimension of sustainability, ensuring that the evaluation reflects the dynamic and complex interplay between project duration, building usage patterns and EC measurement.

$$CiBEC = \frac{EC_N}{F_L \times F_U}$$ Equation (2)

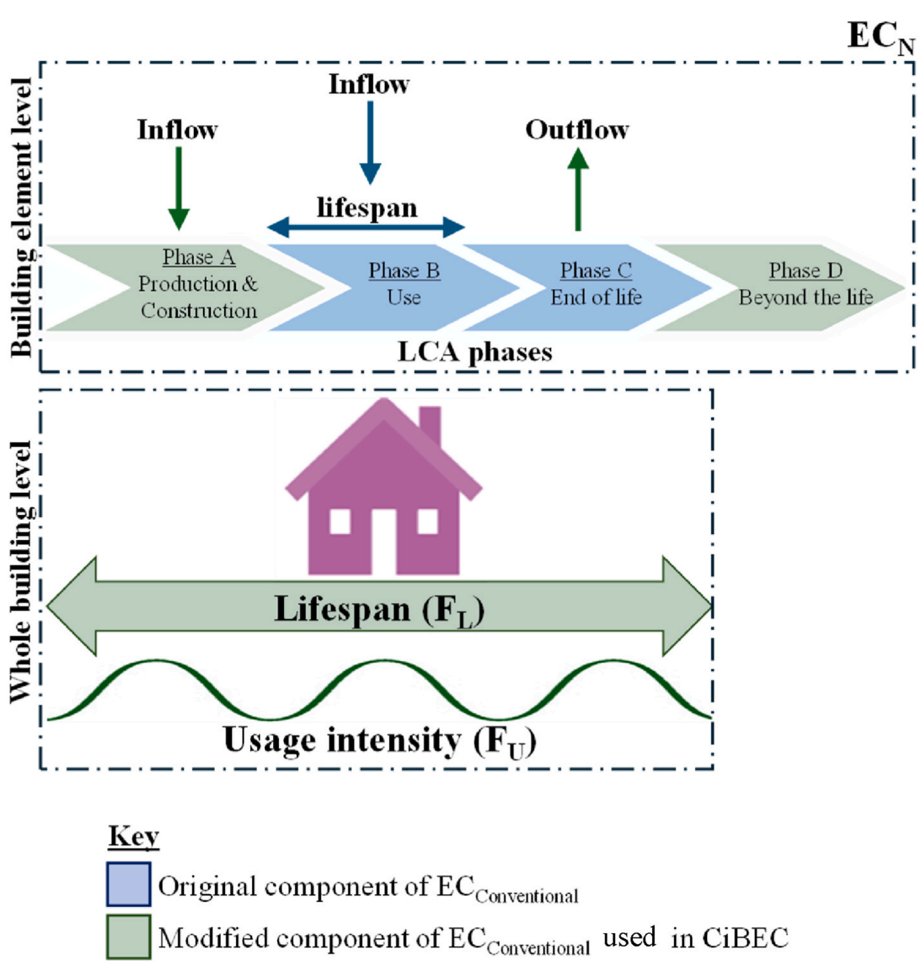

Fig. 1. Different components of EC measurement in the building projects.

Where EC_N is net measured EC generated through scope of the project w, F_L is term of lifespan of the projects, and F_U is the term of usage intensity of projects.

2.1.1. Net measured EC

EC_N incorporates two terms into the $EC_{Conventional}$, as shown in Equation (3): (1) the inflow modification (IM), which is related to the impacts of circular inflow materials, and (2) the outflow modification (OM) which is the impacts of circular outflow materials on the measured EC (naturally has the negative value i.e. saving EC). These terms are defined to enhance the allocation in both inflow and outflow, ensuring fairness, transparency, and equity in resource distribution (Long et al., 2024; Wiedenhofer et al., 2024).

While this study proposes a fair allocation method for both IM and OM, it is important to note that the quality of underlying data can significantly influence the accuracy of EC calculations. The incorporation of quality correction factors (QCFs)—such as those accounting for data source reliability, geographic representativeness, and temporal relevance—can enhance the credibility of inflow and outflow comparisons. Although QCFs were not implemented in the current work, future development of the CiBEC index should consider their integration to adjust embodied carbon values based on the quality-of-life cycle inventory inputs and EPDs.

$$EC_N = EC_{\text{Conventional}} + OM + IM \qquad \text{Equation (3)}$$

To calculate the terms of IM and OM, this study proposes an innovative approach to streamline the assessment process. As illustrated in Fig. 2, two separate models are developed using the same quantity take-off for each circular scenario within the applied software. The first model, referred to the actual model hereafter, possess the materials selected for each scenario, where all inflow resources consist of a mix of virgin and recovered materials. For example, a steel product containing 30 % recycled content is used. The second model, referred to as the virgin model, assumes that all inflow resources are derived entirely from virgin materials, with no recycled, reused, or reclaimed content (e.g. a steel product with 0 % recycled content). It should be noted that other factors, such as transportation distances and energy consumed during production, are held constant between the two models to ensure a fair comparison.

The conventional zero-one allocation approach, where all saved EC beyond the life ($EC_{\text{phase D}}$) is allocated solely to the current project, is modified to a 0.5–0.5 allocation in which half of the benefits are attributed to the current project, and the other half to the next supply chain (see Equation (4)). In this equation $EC_{\text{phase D}}$, referred to as saved EC due to circular outflow, are derived from the LCA results of Model 1 (the actual model). This approach, inspired by (Wang et al. (2023), is used for efforts towards EoL material recovery, such as reusing, recycling, and energy recovery in buildings or their components. These efforts often go unnoticed in LCA (Mirzaie et al., 2020) and are merely considered as a separate credit (Q4 addressed; Ashtiani et al., 2024; Q4 addressed).

$$OM = \sum_{\text{Material}} \frac{EC_{\text{phase D}}}{2} \qquad \text{Equation (4)}$$

Similarly, to calculate the impact of circular inflows, primarily affecting phases A1 to A3 of the material lifecycle, a 0.5–0.5 allocation is applied for the saved carbon, rather than assigning the entire benefit to the current project. Based on the carbon mass balance which all generated carbon should be allocated in all particular activities, projects or processes, this allocation acknowledges the circular efforts made by previous projects or third-party industrial sectors, such as the steel production industry or companies processing demolished concrete and secondary raw timber-based products, to manufacture new products from recycled content for use in the current project (Wang et al., 2023).

To implement this allocation, Equation (5) is used to calculate the carbon benefit of circular inflows. This benefit is determined by subtracting the embodied carbon of production phase (phases A1 to A3) in Model 1 (refer to Fig. 2) which is the actual model (referred to as $EC_{\text{product mix}}$ in the equation) from that in Model 2 (See Fig. 2) in which the virgin model is documented (referred to as $EC_{\text{product virgin}}$ in the equation). The difference represents the carbon savings achieved through the use of circular materials. To apply the 0.5–0.5 allocation, this carbon benefit is then divided equally, with only half attributed to the current project.

$$IM = \sum_{\text{Material}} \frac{\left(EC_{\text{Product virgin}} - EC_{\text{Product mix}}\right)}{2} \qquad \text{Equation (5)}$$

2.1.2. Impacts of building's lifespan of the project

Many strategies within the circular economy for the built environment prioritise extending the assets lifespan (Arup, 2016; Eberhardt et al., 2022). These efforts can impact both the longevity of individual elements/products and the overall lifespan of buildings (Densley Tingley et al., 2018; Konietzko et al., 2020). For instance, renovation or refurbishment projects can prolong the lifespan of entire buildings, while reusing wall panels may extend the lifespan of specific elements (Arup, 2022; Ellen MacArthur Foundation and Arup, 2024). Although the impacts of longevity on elements or products are sometimes considered in certain stages of LCA, notably the replacement stage (phase B4), the effects of circular interventions on the overall longevity of buildings are often neglected in traditional LCA frameworks. These frameworks typically concentrate solely on the functional aspect (kg CO_2 eq./m^2), overlooking the broader impacts of circular strategies on the building's lifespan.

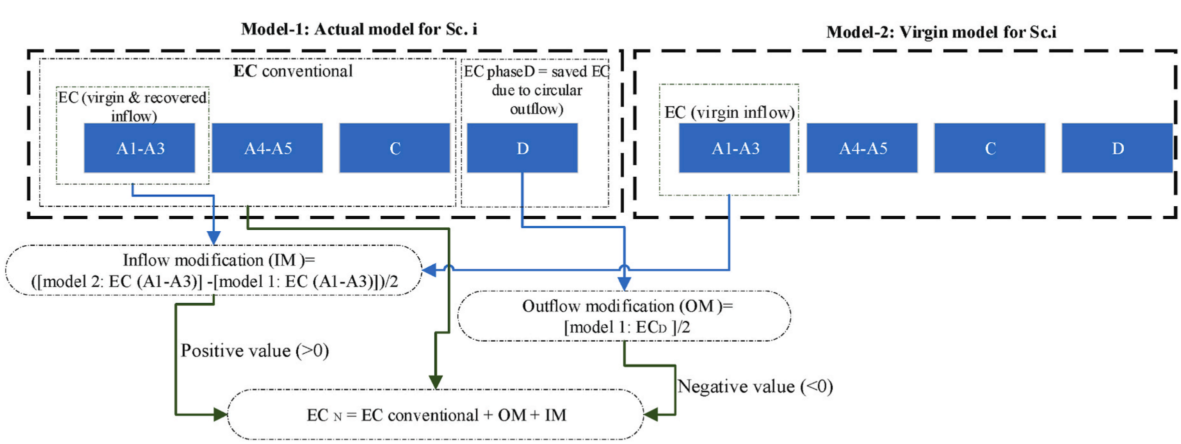

Fig. 2. The process for calculation of IM an OM in the EC_N assessment.

This explains the nature of "F_L" in Equation (3). This term, as shown in Equation (6), is designed to be comparable and reflects the efforts made by proposed alternative circular actions in comparison to the baseline design project. For this purpose, the lifespan of the new proposed option (L_{Sc}) will be divided to the lifespan of the BaU project of the initial design (L_{BaU}). This ratio allows for a comparison between the extended/shrunk lifespan due to circular strategies and the original lifespan design, thereby quantifying the impact of these circular interventions. The units can be expressed on a monthly or yearly scale, depending on the intended timeframe of analysis.

$$F_L = \frac{L_{Sc}}{L_{BaU}} \quad \text{Equation (6)}$$

2.1.3. Building's usage intensity of projects during same lifespan

Many strategies within the circular strategies propose extending the usage intensity of projects without changes in building lifespan. For example, many office buildings operate during regular work hours, typically 8-h shifts. However, if these buildings are used for two shifts each day, the same building can accommodate twice as many companies. While this approach requires careful considerations such as cyber security and social acceptance, it can lead to reduction in new constructions. However, this improvement may not be acknowledged in conventional LCA assessment and consequently is added by including F_u here to CiBEC index. This term, as shown in Equation (7), accounts for the increased building's usage intensity of the new proposed options (U_{Sc}), divided by the initial usage intensity of the BaU project of the initial design (U_{BaU}).

As noted in the literature (Ellen MacArthur Foundation, 2015; WBCSD, 2022), the unit of usage intensity can vary depending on the nature of the asset and the type of circular strategy implemented. For example, usage may increase through longer operational hours (a time-based unit) or through higher occupancy (a population-based unit). To address this variability and enable meaningful comparisons across scenarios, usage intensity is normalised by expressing U_{Sc} relative to U_{BaU}.

$$F_u = \frac{U_{Sc}}{U_{BaU}} \quad \text{Equation (7)}$$

2.2. Case study application

CiBEC is applied for a real case study to validate the proposed index. The baseline project examines the EC footprint of a 7-story office building currently in the design phase in Tehran, Iran. The building comprises 10 office units spread across six floors, with parking facilities located in the basement and ground floor. Its total gross floor area spans 2230 m^2. The building's characteristics, including its function, size, and structural system, are drawn from BaU practices (Izaola et al., 2023). It features separate units with minimal shared spaces. Each unit is equipped with dedicated zones for focused work, collaboration, meetings, and socialising. Each office unit operates independently and is occupied by a single company on weekdays during standard business hours.

The building's structure consists of a concrete framework designed in accordance with national codes (Iran Ministry of Roads and Urban Development, 2020), with a primary focus on meeting seismic criteria for a lifespan of 50 years (Iran Ministry of Roads and Urban Development, 2016). There is limited consideration given to future scenarios, such as changes in usage type or the need for multifunctional designs. Regarding being located in a high-risk seismic zone, the structural system employs reinforced moment frames combined with shear walls to minimise the size of structural elements. Two-way reinforced slabs are commonly used for roofs, engineered to support heavy loads in both directions. While effective in bearing loads, slabs have limited span lengths, imposing constraints on the configuration and layout of floor plans. Additionally, traditional construction methods prevalent in the region contribute to challenges regarding non-structural elements (Delnavaz et al., 2023).

As shown in Table 1, internal walls are typically constructed using in-situ materials like autoclaved aerated concrete (AAC) blocks and gypsum covers. These elements lack modularity and offer little flexibility for future office layout alterations once installed. Furthermore, due to the availability of natural stone and aesthetic preferences, facades are constructed using natural slabs installed with cement mortar on-site (Jalali et al., 2019), which means that any future renovations or alterations would necessitate the complete deconstruction of these facades, adding complexity and cost to such endeavours.

A significant portion of materials ends up in landfills during the construction and demolition waste management process. This trend is influenced by market considerations such as material pricing and availability, economic justifications due to recycling costs, and logistical barriers stemming from deficiencies in downstream infrastructures. Diverse waste streams, ranging from hard cores and plasters to glass and even reinforced rebars, often remain unsorted, resulting in mixed waste destined for disposal (Zakerhosseini et al., 2023). In concrete buildings, non-structural metal originating from wall posts, frames, and similar components is typically segregated for recycling, primarily due to its economic viability (Khoshand et al., 2020). These prevailing waste management practices lead to a significant reliance on virgin sources for materials, resulting in minimal application of recycled content (Oladazimi et al., 2020).

The collected data are fixed and assumed to be reliable across all scenarios and throughout the project's lifespan. This assumption is primarily based on the approach inspired by Pasanen et al. (2018) and Waldman et al. (2020), whereby the use of generic EPDs is deliberately avoided. Instead, product-specific EPDs are used which are validated and accredited by well-established third-party organisations such as green building councils, ISO, or other relevant frameworks. Furthermore, while OneClickLCA was used for the modelling, all input data were reviewed to ensure they were verified through the software's internal validation process, providing an additional layer of data reliability (OneClickLCA, 2024a, 2024b). For the quantification of materials, best practices that are representative of real-world applications were adopted, with data collected directly from procurement documents to avoid introducing uncertainty into the dataset.

2.2.1. Circular scenario development

The scenarios development is inspired by two widely recognised frameworks: (1) 10R framework adapted from Kirchherr et al. (2017), Potting et al. (2017), and Arup (2022), and (2) circular buildings toolkit adapted from Ellen MacArthur Foundation and Arup. (2024). More details about these two frameworks are provided in the Part 1 and 2 of Appendix for brevity. CSs are limited to manageable number through experts' opinions and relevant direct stakeholders, including academic staffs as part of the R&D section, investors and owners, consultant representatives, general contractor representatives, and presell clients as end-users. These scenarios are evaluated to ensure feasibility, economic justification, accessibility, acceptability, and social consideration are included ensuring that global best practices can be effectively adapted and applied within the context of the case study. As a result, 8 CSs are finalised, as shown in Fig. 3:

- **CS1: Maximising material recovering at the EoL**: This scenario includes: (1) downcycling the concrete (within structure and substructure elements) through crashing and using as aggregate, (2) downcycling AAC, ceramic tiles, and natural stones through crashing and using in backfills aggregate, and (3) recycling rebars from concrete. In this scenario, the outflow streams from elements such as substructure, structure, enclosure, and finishing will be impacted. This will result in an increase in EC in stage C due to additional treatments, and an increase in saved carbon in stage D due to the material's circulation.

Table 1
Main BaU element building design characteristics for baseline project.

Item	Structure		Encloser		Finishing					
	Vertical	Horizontal	External walls	façade	Internal walls	Wall cover	Flooring cover	Ceiling Cover	Insulation	Windows
Technology[a]	RC column, shear wall	RC beam, decks, stairs	Permanent AAC-blocks walls Steel frame for wall-posts with no thermal insulation	Natural stone, cement mortar Steel frame for façade Under and top coat layer of exposed cement mortar	As external walls	Gypsum Bathroom and kitchen: ceramic tiles with cement mortar Parking, stairs, and balcony: Natural stone with cement mortar	Under layer: foam-create Rest as wall cover	Galvanised steel framed plasterboard ceiling	Thermal insulation for roof and basement: Polyurethanes in Multi-layer bitumen Moisture insulation: Bitumen waterproofing in floors	Mixed double glased Aluminium framed PVC
Inflow[b]	As Retaining walls	As Retaining walls	AAC: 100 % VM Steel frame 40 % RM	Steel frame 40 RM Rest: 100 % VM	As external walls	100 % VM	100 % VM	15 % RM galvanises steel 10 % RM gypsum plaster board	20 % RM XPS, Rest 100 % VM	100 % VM
Outflow[c]	L	L	R for steel, L for rest	R for steel, L for rest	R for steel, L for rest	L	L	R for steel, L for rest	L	L
lifespan (Years)	As building	As building	As building	50	25	50	Ceramic: 25	25	XPS: 30	50

[a] RC: Reinforced concrete AAC: Autoclaved aerated concrete.
[b] RMC: Ready-mix concrete VM: Virgin material.
[c] L: Landfilling R: Recycling.

- **CS2: Reuse, renovate or repurpose an existing asset:** This scenario includes renovating the building finishing (excepting foam-crete in floors, natural stone in common areas, and thermal insulation) after 50 years instead of demolishing. This action affects the finishing elements' inflow due to using new materials, outflow of demolished elements, and life span of new materials. Besides it was estimated that life span can be extended to 80 years.
- **CS3: Increasing the multi-use potential of building spaces:** This scenario, increases the building's usage by adding an additional 8-hr shift for companies that operate outside regular office hours. For instance, trading companies that work at night due to time zone differences with international markets. The same building can host twice as many companies, reducing the need for new constructions. While requiring careful consideration of factors such as privacy and social acceptance, implementing this approach can be achieved by integrating co-working spaces with flexible layouts, complemented by open floor plans featuring designated areas for focused work, collaboration zones, and social areas. In this scenario usage intensity will be doubled ($F_U = 2$). However, the life span of building is decreased by 10 years ($F_L = 0.8$) due to increased intensity of usage.
- **CS4: Design for an increased utilisation of regularly empty spaces:** This scenario suggests eliminating some private meeting and connection areas from the units (approximately 207 m^2) and creating a shared break room along with two shared meeting/conference rooms (107 m^2). The remaining areas of the units would be allocated to focused work and collaboration. Additionally, adding another unit (100 m^2) on the ground floor would be possible according to construction permission and parking considerations. This approach would accommodate up to 11 companies, resulting in a 10 % increase in usage intensity compared to the BaU scenario ($F_U = 1.1$). In addition, this change would impact inflows, particularly in finishing elements, due to alterations in the interior design and material quantities.
- **CS5: Make use of versatile/flexible/movable internal walls for the space layout to support multi-use:** This scenario replaces permanent AAC internal walls with flexible, disassemble-ready, and modular wooden walls. The use of gypsum for wall covering is reduced by 70 % and impacts the outflow and lifespan of the elements due to the shift in material type. The lifespan of the wooden walls was assumed to be 50 years, considering their reusability, and they were assumed to be landfilled at the EoL.
- **CS6: Maximise the use of reclaimed components for all building layers:** This scenario maximises the use of reclaimed components, increasing the recycled content in consumed steel. The recycled content for rebars, steel frames in walls and façade, and galvanised steel in ceilings' structure is enhanced to 60 %, 80 %, and 70 %, respectively, through more responsible sourcing. This action will affect inflow of all elements.

-CS7: Use bio-based rapidly renewable materials for the interior design concept: This scenario involves replacing flooring tiles with wooden parquet tiles which changes the inflows in floor covering by substituting ceramic tiles and cement mortar with wooden parquet. The change in material type and its final disposal, assumed to be landfill, also impacts the outflow of this element. The lifespan of the wooden tiles is assumed to be equivalent to tiles based on local EPDs.

- **CS8: Replacing the carbon-intensive materials:** This scenario replaces 50 % of Portland cement in substructure and structure's concrete with Ground Granulated Blast-furnace Slag (GGBS), leading to altering inflows in these elements, according to the available local technologies as well as design considerations.

2.2.2. *Combined scenarios development*

Combined scenarios have been developed to compare the impact of various strategies affecting inflow, outflow, building's usage intensity, and building's lifespan, as outlined in Table 2: (Comb1): Direct effect on

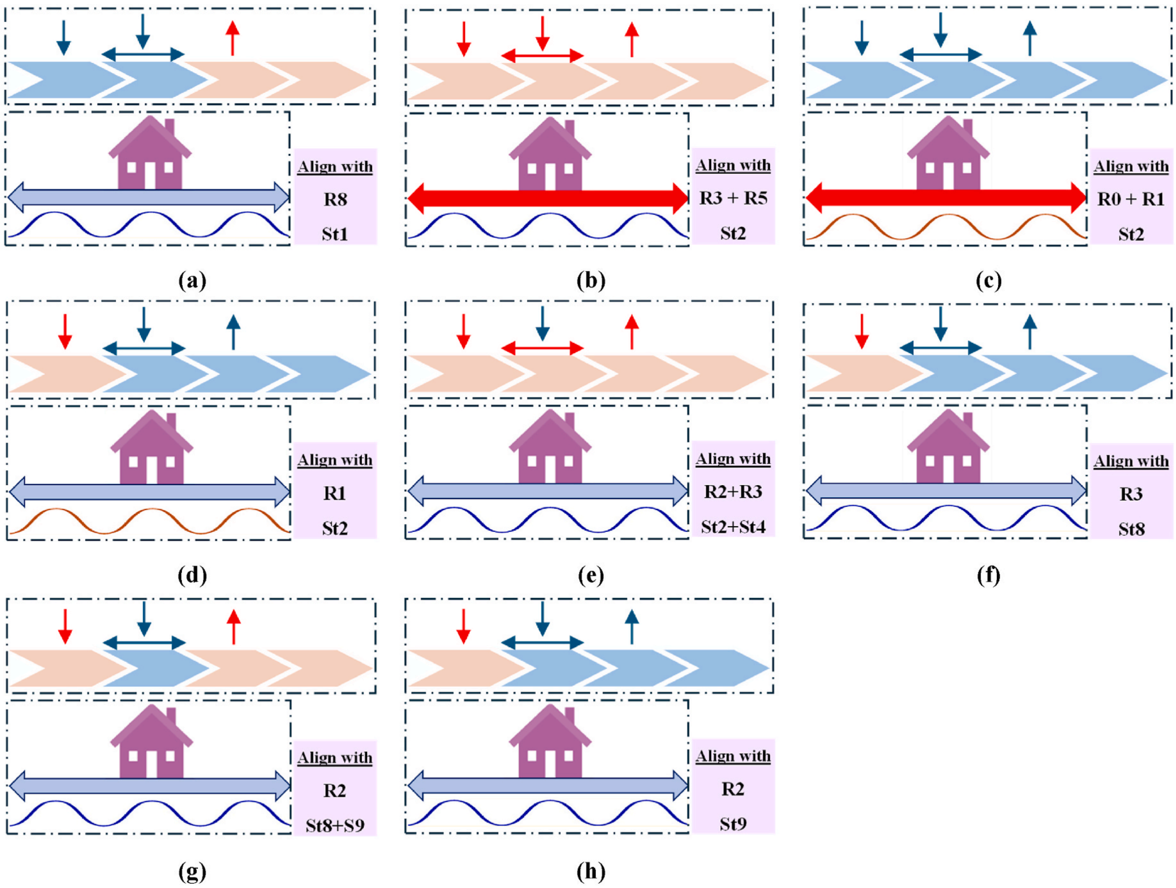

Fig. 3. Developed scenarios for CE actions (Description of symbols of R and St frameworks are provided in the Appendix parts 1 and 2 for brevity): (a) CS1: Maximising material recovering at the EoL, (b) CS2: Reuse, renovate or repurpose an existing asset, (c) CS3: Increasing the multi-use potential of building spaces, (d) CS4: Design for an increased utilisation of regularly empty spaces, (e) CS5: Make use of versatile/flexible/movable internal walls for the space layout to support multi-use, (f) CS6: Maximise the use of reclaimed components for all building layers, (g) CS7: Use bio-based rapidly renewable materials for the interior design concept, (h) CS8: Replacing the carbon-intensive materials.

Table 2
Defined combined circular scenarios.

Name	Code	Combined scenarios
Direct effect on inflow	Comb1	CS5+ CS6 + CS7 + CS8
Direct effect on both inflow and outflow	Comb2	CS1+ CS5 + CS6 + CS7 + CS8
Direct effect on building's usage intensity	Comb3	CS3 + CS4
Direct effect on both intensity, and building's life span	Comb4	CS2 + CS3 + CS4
Direct effect on inflow, EoL outflow, and buildings life span	Comb5	CS1+ CS2 + CS5 + CS6 + CS7 + CS8
Direct effect on inflow, EoL out flow, and usage intensity	Comb6	CS1+ CS3 + CS4 + CS5 + CS6 + CS7 + CS8
Direct effect on inflow, EoL out flow, usage intensity and building's life span	Comb7	CS1+ CS2 + CS3 + CS4 + CS5 + CS6 + CS7 + CS8

inflow, (Comb2) Direct effect on both inflow and outflow, (Comb3): Direct effect on building's usage intensity, (Comb4): Direct effect on both usage intensity, and building's life span, (Comb5): Direct effect on inflow, EoL outflow, and buildings life span, (Comb6): Direct effect on inflow, EoL out flow, and usage intensity, and (Comb7): Direct effect on inflow, EoL out flow, usage intensity and building's life span. It's crucial to note that combining scenarios creates entirely new scenarios that necessitate redefining all factors, as these combinations do not exhibit linear regression.

2.2.3. Analysis implementation

Attributional LCA is employed here through using the OneClick LCA software with an expert research license. The system boundaries for the LCA, detailed in Table A2 of the appendix, include sub-structure, structure, enclosure, and finishes. This delineation follows the methodology recommended by Mirzaie et al. (2020), providing guidelines for determining which building elements should be included or excluded when assessing circularity in comparative building LCAs. This assessment also was conducted from cradle to cradle, based on recommendations of EN 15978 where operational carbon and water consumption are excluded (Hasik et al., 2019a). To minimise uncertainties, efforts were made to use local EPDs within OneClick LCA. When local EPDs were unavailable, regional EPDs were applied and then localised by using the software presets. Transportation routes, including urban, motorway, and road paths, were meticulously selected for each material based on the most probable journey from the factory to the construction site, with distances calculated using Google Earth pro. Energy consumption considerations were included to ensure that energy efficiency and occupant comfort were consistent across all scenarios (Bragadin et al., 2023).

F_U and F_L factors are added after extracting results from software. For EC_N calculation, the project required modelling each scenario twice using software (see Fig. 2), encompassing: (1) the actual model, where all resources, their lifespans, and their EoL stages are defined according to the scenario's assumptions, and (2) the virgin model, similar to the actual model but differs in that it uses entirely virgin resource inflows. This doubled analysis is for calculating the IM using Equation (4) by subtracting the EC product virgin in virgin model from the EC product mix of the actual model. Additionally, the OM is calculated through the EC phase D of the actual model using Equation (5).

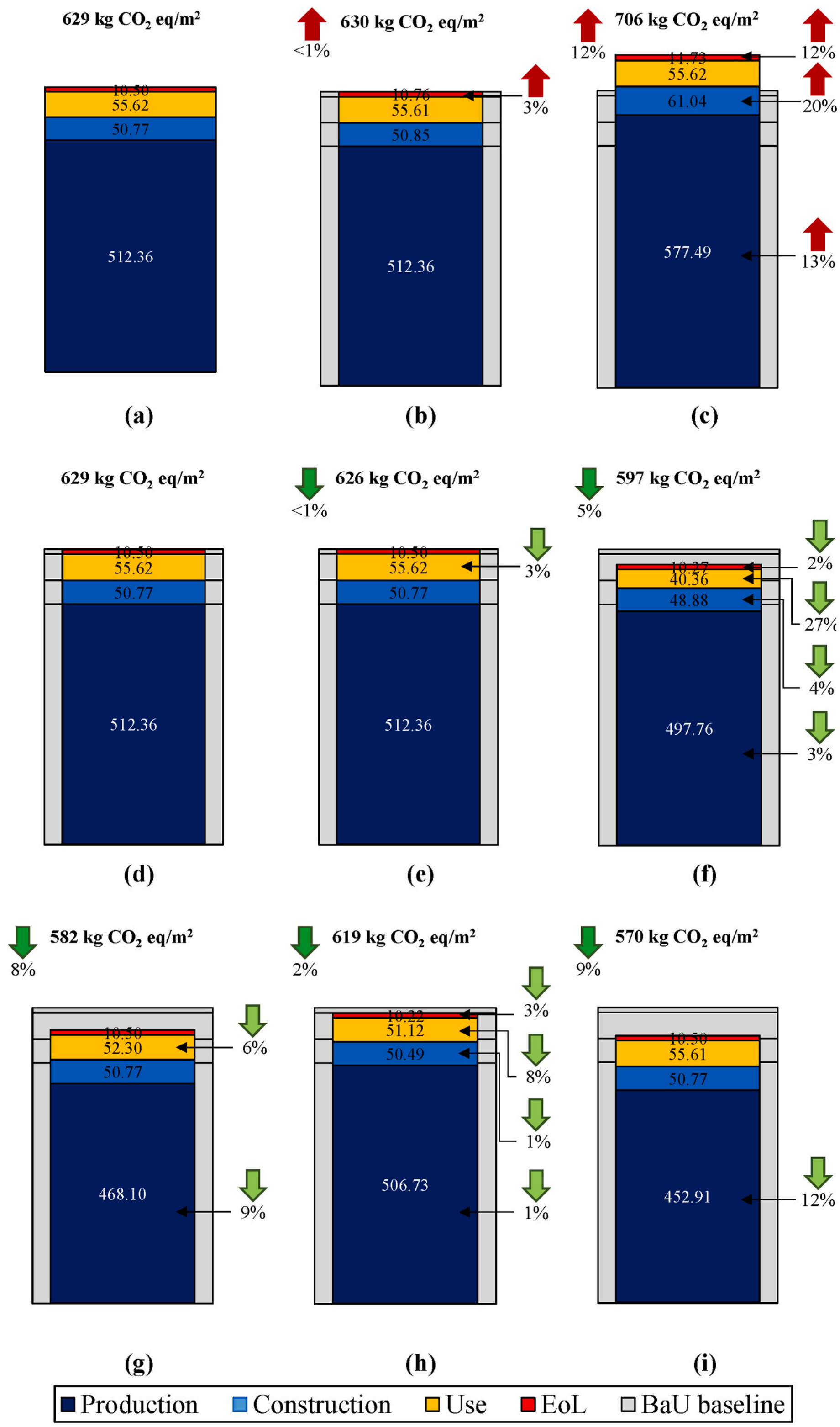

Fig. 4. EC measured for each scenario based on EC conventional index: (a) Business as usual, Bau, (b) CS1: Maximising material recovering at the EoL, (c) CS2: Reuse, renovate or repurpose, (d) CS3: Increasing the multi-use of building spaces, (e) CS4: Increased utilisation of regularly empty spaces, (f) CS5: Use of versatile/flexible/movable internal walls, (g) CS6: Maximise the use of reclaimed components, (h) CS7: Use bio408 based rapidly renewable materials, (i) CS8: Replacing the carbon-intensive materials.

3. Results and discussion

3.1. Circular scenarios contribution based on conventional approach

Fig. 4 (raw data are provided in Table A3 in the Appendix) demonstrates how different scenarios affect the conventional cradle to grave EC and the variations in carbon generation across various phases. The red arrows highlight increases in carbon emissions, the green arrows denote decreases, and the black arrows indicate the overall percentage change in EC for each scenario. BaU scenario (Fig. 4a) with an EC of 629 kg CO_2eq./m^2, serves as the baseline for demonstrating EC changes due to circular actions. CS1 (Fig. 4b), attempting to circulate material at the EoL, results in a negligible change in EC and even an increase in the EC of EoL (3 %) due to the additional processing required for recycling. The conventional cradle-to-grave framework fails to account collectively for the carbon savings achieved by recovering materials at EoL. Considering the building as a bounded system, CS2 (Fig. 4c), which involves renovating the building at the end of its life, shows a considerable increase of 12 % in total EC and significant rises in various phases. This increase results from the inflow of new materials during the renovation process.

Although the building's lifespan would be extended and the total EC would be distributed over a longer period, this effect cannot be

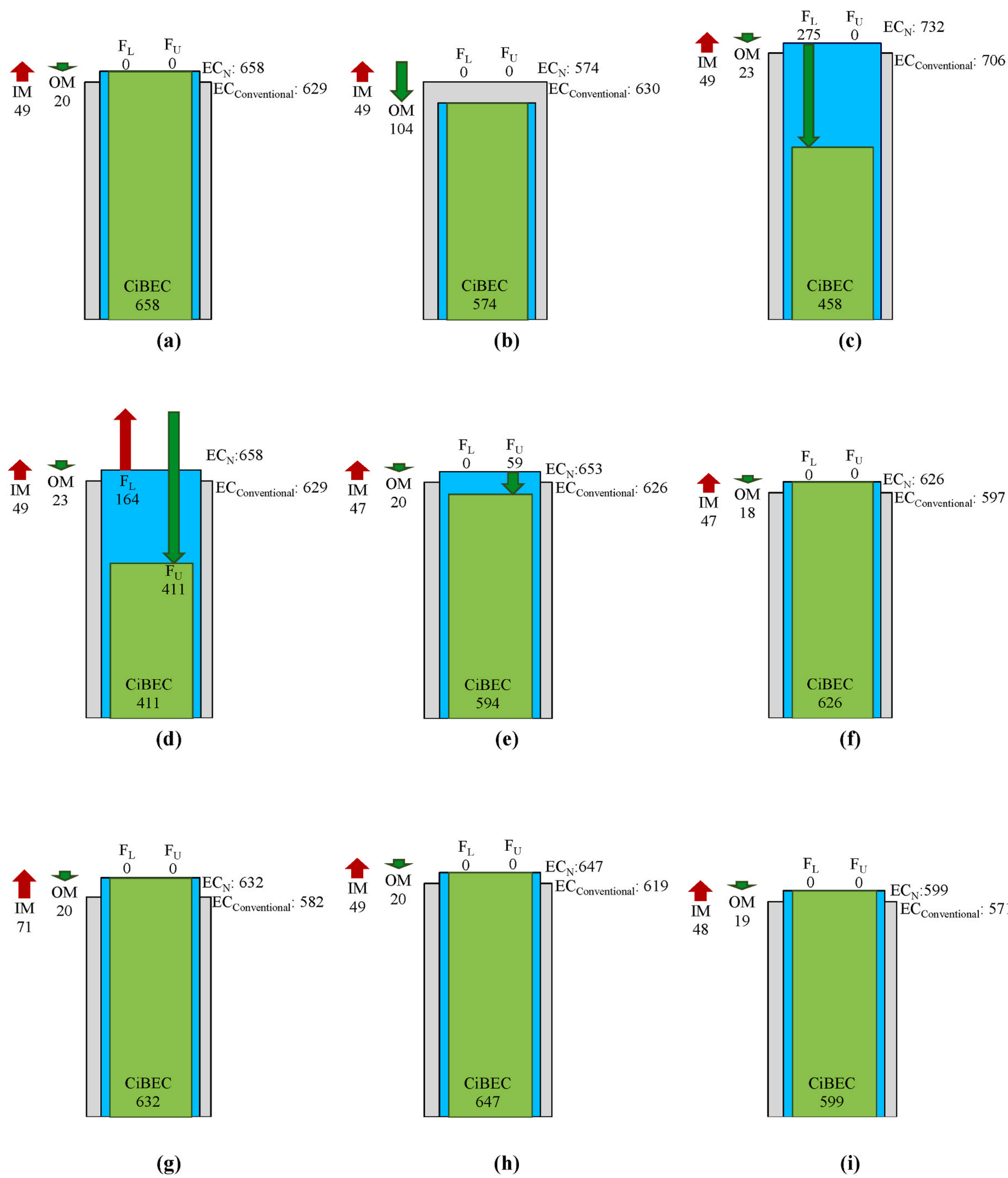

Fig. 5. EC measured for each scenario based on proposed index: (a) Business as usual, Bau, (b) CS1: Maximising material recovering at the EoL, (c) CS2: Reuse, renovate or repurpose, (d) CS3: Increasing the multi-use of building spaces, (e) CS4: Increased utilisation of regularly empty spaces, (f) CS5: Use of versatile/flexible/movable internal walls, (g) CS6: Maximise the use of reclaimed components, (h) CS7: 460 Use bio-based rapidly renewable materials, (i) CS8: Replacing the carbon-intensive materials.

accounted for in the conventional framework. Furthermore, as the EC of the CS3 (Fig. 4d) would appear the same as BaU due to similar inflows and outflows, the conventional framework also fails to capture the impact of multi-usage, which avoids new construction by enhancing usage intensity of the building through unit sharing. Similarly, CS4 (Fig. 4e) achieves only a marginal 1 % reduction in EC, neglecting to account for the carbon savings from reallocating space and reducing underutilised meeting and connection areas, while also being added an additional unit.

Replacing permanent AAC internal walls with flexible, disassemble-ready, and modular wooden walls in CS5 (Fig. 4f) results in a total 5 % reduction in EC, with small reductions in phases A (7 %) and C (2 %), while a significant reduction in phase B by 27 % due to reduced material replacements in reusable wooden walls. What the conventional framework overlooks in this scenario is the carbon savings that could be achieved from reusing these walls beyond the building's lifespan. Similarly, while the framework accounts for a 2 % carbon reduction from using low-carbon biobased inflow materials in SC7 (Fig. 4h), and a 9 % carbon reduction from substituting low-carbon materials for carbon-intensive cements in SC8 (Fig. 4i), it neglects to consider carbon saving beyond project. Furthermore, in CS6 (Fig. 4g), although the conventional framework acknowledges an 8 % reduction in EC from using reclaimed inflow materials, it may not accurately allocate all saved carbon to the current system.

3.2. Circular scenarios contribution based on CiBEC index

Fig. 5 illustrates the proposed CiBEC index (green column) and the impact of its components: IM, OM, F_L, and F_U. These components take into account the effects of circular actions that conventional cradle-to-grave EC (gray columns) may fail to account. Besides, the EC_N (blue column) represents the total net carbon after considering and allocating the saved carbon in inflow and outflow by IM and OM, in each scenario. In the BaU (Fig. 5a), the fairer allocation of saved carbon in both inflow and outflow leads to an increase of 49 kg CO_2 eq./m^2 in IM and a decrease of 20 in OM, resulting in a net EC (EC_N) of 658. Then the comparative factors of F_L and F_U in this scenario are 1, as they are compared to themselves, making CiBEC equal to EC_N at 658. For comparative analysis, CiBEC in the BaU should be used as the baseline instead of the conventional EC.

In CS1 (Fig. 5b), CiBEC decreases to 574, a 13 % reduction compared to no reduction in BaU. This reduction is due to OM improving by 84 units less than BaU, thanks to recovery efforts at EoL. In contrast, this effort has a negligible impact on conventional EC. In SC2 (Fig. 5c), extending the building lifespan to 80 years through renovation, increases EC_N due to new material inflows, but change in F_L ($F_L = 80/50 = 1.6$) reduces CiBEC to 458, a 30 % reduction from BaU, whereas conventional EC shows a 12 % increase. CS3 (Fig. 5d), involving a sharing action that doubles the building's usage intensity ($F_U = 2/1 = 2$) while decreasing its lifespan to 40 years due to severe depreciation ($F_L = 40/50 = 0.8$), results in a CiBEC of 411 units, a 37 % carbon reduction. In contrast, the impact of this action on conventional EC is zero, as the inflows and outflows remain similar. Similarly, in CS4 (Fig. 5e), reducing underutilised meeting and connection areas increases usage intensity to 1.1 by adding 1 office unit (F_U = 11unit/10 unit = 1.1), resulting in a CiBEC of 594, a 10 % carbon reduction, while having a negligible impact on conventional EC.

In CS5 (Fig. 5f), similar to conventional EC, CiBEC accounts for carbon reduction in usage phase by extending wall elements' lifespan, while the building's overall lifespan remains constant ($F_L = 1$), and in phase A by using lower carbon-intensive biobased materials, resulting in a total carbon reduction of about 5 %. Similarly, in SC7 (Fig. 5h), using low-carbon biobased inflow materials, and in SC8 (Fig. 5i), substituting low-carbon materials for carbon-intensive cements, decrease EC in phase A, resulting in 2 % and 9 % carbon reductions, respectively. Finally, in CS6 (Fig. 5g), while conventional EC acknowledges an 8 % reduction mainly from production phases due to using reclaimed inflow materials, this reduction is not wholly assigned to current building by CiBEC. Instead, CiBEC, using a modification in saved carbon in inflow, shows a fairer and more accurate 4 % reduction.

3.3. Comparison of proposed index with conventional approach

Fig. 6 compares various scenarios within two frameworks of conventional EC and CiBEC index. In each matrix, the values represent the relative EC (emission coefficient) of the scenario in the column compared to the scenario in the row. The first row in both frameworks show the impact of each circular action (scenario) on EC relative to the BaU scenario (baseline). Significant differences are observed in CS1, CS2, CS3, CS4, and CS6. In the conventional EC framework (Fig. 6a), CS2 shows a 12 % increase in EC, while CiBEC shows a 30 % reduction due to accounting for the building's life span. CS3 shows no change in conventional EC but a 37 % reduction in CiBEC, considering rise in building's usage intensity. Similarly, CS4 shows a 10 % performance difference due to usage intensity considerations, and CS1 indicates a 13 % reduction in CiBEC, due to the inclusion of saved carbon from recovery efforts at the EoL. CS6 shows a 4 % improvement in CiBEC versus 8 % in conventional EC, reflecting a fairer carbon savings allocation between previous stakeholders and the current system at inflow.

These scenarios demonstrate CiBEC's advantages in accounting for the impact of circular efforts, particularly in situations involving changes in building life span, usage intensity, the use of products with recovered/reclaimed material inflow and recovering outflow materials at EoL. Therefore, the frameworks provide different prioritisation: CiBEC ranks CS3 (37 % reduction), CS2 (30 % reduction), and CS1(13 % reduction) as the top scenarios for carbon reduction, whereas the conventional framework ranks CS8, CS6, and CS5 as the best, with CS2, CS1, and CS3 at the bottom. This illustrates that the new index can yield different and sometimes contradictory results for decision-making process.

3.4. Combined scenarios analysis

Table 3 illustrates the effect of combining circular actions on EC reduction. The first takeaway from this analysis is that the overall carbon reduction in a combined scenarios is not merely the sum of reductions from individual scenarios. This is because new combinations create new scenarios with unique assumptions that must be modelled anew. For example, in the combined scenario of Comb3, which merges CS3 and CS4, the factor F_U is assumed anew amount of 2.2 ($F_{U(CS3)} \times F_{U(CS4)} = 1.1 \times 2$). The CiBEC reduction in Comb4 rather baseline is 43 %, whereas the individual reductions for CS3 and CS4 are 37 % and 10 %, respectively. Furthermore, comparing the CiBECs shows that scenarios Comb7 i.e. including all interventions in inflow, outflow, EoL, usage intensity and building's life span can significantly reduce the EC to only 191 (with a 71 % reduction) mainly because of impacts of F_L and F_U. Moreover, by combining circular actions, the EC can be reduced by up to 71 % (in scenario Comb7), which is significantly larger than the best individual scenario (CS3) with a 37 % reduction.

3.5. Contribution and novelty

Although prior studies have recognised the potential of circular strategies to reduce embodied carbon (e.g., Andersen et al., 2020; Densley Tingley et al., 2018; Hasik et al., 2019), they typically evaluate these strategies in isolation and within determined LCA boundaries. However, CE actions inherently modify these boundaries, particularly by extending building lifespans, intensifying usage, and redistributing carbon savings across projects and life cycle phases. In contrast, the CiBEC index introduced in this study captures these dynamics through a cradle-to-cradle perspective and a fairer allocation of carbon benefits across phases A and D. By integrating lifespan and usage intensity as

	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8
BaU	1.00	1.12	1.00	0.99	0.95	0.92	0.98	0.91
CS1		1.12	1.00	0.99	0.95	0.92	0.98	0.91
CS2			0.89	0.89	0.85	0.82	0.88	0.81
CS3				0.99	0.95	0.92	0.98	0.91
CS4					0.95	0.93	0.99	0.91
CS5						0.97	1.04	0.95
CS6							1.06	0.98
CS7								0.92

(a)

	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8
BaU	0.87	0.70	0.63	0.90	0.95	0.96	0.98	0.91
CS1		0.80	0.72	1.03	1.09	1.10	1.13	1.04
CS2			0.90	1.30	1.37	1.38	1.41	1.31
CS3				1.44	1.52	1.54	1.57	1.46
CS4					1.05	1.07	1.09	1.01
CS5						1.01	1.03	0.96
CS6							1.02	0.95
CS7								0.93

(b)

Fig. 6. Matrix of relative EC generated normalised based on BaU scenario: (a) Conventional EC measurement, (b) CiBEC index (Green cells indicate a relative decrease in EC, signifying a reduction in carbon emissions, whereas red cells indicate a relative increase in EC. The intensity of the colour corresponds to the magnitude of the relative change, with darker colours indicating greater relative improvement -green- or deterioration-red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
EC measured for each scenario based on proposed index.

Scenario	$EC_{Conventional}$ (Kg/m^2)	IM and OM (Kg/m^2)	F_L and F_U (Kg/m^2)	CiBEC (Kg/m^2)
BaU	629	+29	0	658
Inflow effect	492	+55	0	547
Inflow and outflow effect	482	-15	0	497
Building's usage intensity effect	626	+27	-282	371
Intensity, and building's life span effect	704	+25	-470	259
Inflow, EoL outflow, and buildings life span effect	538	+15	-207	346
Inflow, eol out flow, and usage intensity effect	471	+7	-210	277
All effects	522	+15	-346	191

quantifiable factors, CiBEC addresses a key methodological gap in traditional LCA models, offering a more system-wide and equitable assessment of circular interventions.

Furthermore, while the PEF methodology offers a harmonised approach to assessing environmental performance and circularity at the product level, its applicability to complex systems such as buildings is limited. The CiBEC index complements and extends the core principles of PEF, particularly inflow and outflow accounting, by tailoring them to the building scale. Importantly, CiBEC incorporates temporal dimensions of circularity through the explicit integration of building lifespan and usage intensity, factors not directly considered in the PEF framework.

The practical outcomes of applying the CiBEC index also reveal significant differences from conventional assessments, as shown in this study's real-world case analysis. For instance, scenarios such as increased usage intensity or building renovation, which are undervalued or even penalised under traditional frameworks, demonstrate significant EC reductions, up to 37 % and 30 %, respectively, when assessed through CiBEC. This complexity and depth are largely missing in prior research. Therefore, the proposed CiBEC index offers a novel and operationally meaningful pathway for early design-phase decision-making, enabling stakeholders to identify and prioritise high-impact circular interventions.

4. Research limitations and future directions

This study validates its proposed framework and index improvements using a single real-world case study to demonstrate the potential of the approach. However, to offer broader and more generalisable recommendations, it is necessary to test the framework on similar buildings from different countries. Additionally, applying it to other building types could provide valuable insights, though it is understood that the proposed initiatives and circular actions would need to be tailored to each specific case to identify the most effective solutions. Expanding the number of case studies would also support the development of a comprehensive database, ultimately contributing to the creation of a widely applicable toolkit.

While this study focuses on the environmental dimension, the proposed index is defined as a singular variable - the reduction of embodied carbon through circular strategies – and does not account for cost-effectiveness or the potential data uncertainties related to implementation costs. However, evaluating economic feasibility is crucial to support the practical adoption of such strategies. Therefore, future research should incorporate cost-benefit analysis to assess the financial viability of various circular initiatives. Additionally, social aspects such as user comfort, privacy, and social acceptance can be systematically assessed using Social LCA or stakeholder-based surveys. These methods can help quantify the social implications of circular strategies, particularly those involving shared space usage, by capturing user preferences and equity considerations. This could transform the proposed index from a single objective to a multi-objective or multi-attribute decision support system and suggested as future direction. Moreover, applying data uncertainty techniques - such as Monte Carlo simulation and scenario analysis—could enhance the robustness of the EC - related findings, particularly in cases involving assumptions, scenario-based inputs, or where EPDs and validated data are still lacking.

Additionally, future development of the CiBEC index could benefit from incorporating quality correction factors (QCFs). While not applied in this study, QCFs are essential for adjusting embodied carbon values based on the reliability, representativeness, and transparency of input data, particularly in LCA datasets. Their inclusion would enhance the robustness of scenario comparisons and ensure that carbon reduction claims are grounded in data of verifiable quality. This is particularly important when relying on EPDs with varying degrees of precision or when merging datasets from multiple sources with different levels of granularity.

Finally, for some scenarios, the impact on operational carbon would be increased largely. For example, when shifting from a single-building, single-shift model to a two-shift model in the same building, operational carbon would typically double. However, this should be compared with the alternative scenario of constructing a second building to accommodate the second shift, which would result in similar or even higher operational carbon emissions. However, it is understandable that certain shared-space scenarios, such as the one presented in Fig. 5c, could slightly reduce operational carbon due to efficiencies like shared lighting, heating, and cooling in common areas. These reductions represent an additional benefit of such strategies and should be added to measuring total carbon emission of the project. Therefore, to provide more comprehensive assessment, including impact of circular actions should be added to EC as well.

5. Conclusions

This study introduces a simple yet innovative index for measuring EC in building projects, integrating circular actions at four levels: inflow materials, outflow materials, building usage intensity, and lifespan. This index enables project designers and managers to refine designs early and monitor EC throughout the project. Demonstrated with a real-case office building, the index applies to various structures, including residential, commercial, industrial, and institutional buildings. Though primarily designed for building projects, it extends to communities and aligns with green building rating systems like BREEAM and LEED. Its modular framework supports different LCA scopes, from cradle-to-gate to cradle-to-cradle, with the most comprehensive results achieved in a cradle-to-cradle approach.

The results demonstrate the significant impact of the new index by acknowledging circular activities. While some new circular scenarios, such as reusing/renovating/repurposing an existing asset and the multi-use potential of building spaces initially appear to have negative impacts when assessed through conventional methods, this new perspective reveals a reduction in EC measurement.

Further analysis of combination scenarios highlights the substantial decrease in EC measurement achieved through circular actions related to increasing the lifespan of buildings and optimising usage intensity. However, it is important to note that this reduction cannot be simply considered as the sum of the reductions in each individual circular scenario.

As a limitation of this assessment, and as a direction for future research, it is recommended to include other measurements, particularly costing and timing of the alternatives. This will ensure that EC reduction is not only environmentally beneficial but also cost-effective and manageable within the time and scope of the projects.

CRediT authorship contribution statement

Mohsen Ahmadi: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Asal Pournaghshband:** Writing – review & editing, Resources, Formal analysis. **Farzad Piadeh:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation. **M. Reza Hosseini:** Writing – review & editing, Software, Investigation.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145909.

Data availability

Data will be made available on request.

References

Ahmadi, M., Piadeh, F., Hosseini, M.R., Zuo, J., Kocaturk, T., 2024. Unraveling building sector carbon mechanisms: critique and solutions. Renew. Sustain. Energy Rev. 205, 114873. https://doi.org/10.1016/j.rser.2024.114873.

Andersen, C.M.E., Kanafani, K., Zimmermann, R.K., Rasmussen, F.N., Birgisdóttir, H., 2020. Comparison of GHG emissions from circular and conventional building components. Build. Cities 1 (1), 379–392.

Arenas, N.F., Shafique, M., 2024. Reducing embodied carbon emissions of buildings–a key consideration to meet the net zero target. Sustainable Futures 7, 100166. https://doi.org/10.1016/j.sftr.2024.100166.

Arup, 2016. The Circular Economy in the Built Environment [Online] Available at:. www.Arup.com. (Accessed 10 February 2024).

Arup, 2022. Circular fit-out in Retail Stores: Circular Design Principles [Online] Available at: www.Arup.com.

Ashtiani, M., Palmeri, J., Simonen, K., 2024. End of life modeling and data in north American whole building life cycle assessment tools. http://hdl.handle.net/1773/51283.

Blay-Armah, A., Bahadori-Jahromi, A., Mylona, A., Barthorpe, M., 2024. An LCA of building demolition waste: a comparison of end-of-life carbon emission. Proc. Instit. Civil Eng. Wast. Res. Manag. https://doi.org/10.1680/jwarm.22.00012.

Bocken, N.M.P., De Pauw, I., Bakker, C., Van Der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33 (5), 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Bragadin, M.A., Guardigli, L., Calistri, M., Ferrante, A., 2023. Demolishing or renovating? Life cycle analysis in the design process for building renovation: the ProGETonE case. Sustainability (Basel) 15 (11), 8614. https://doi.org/10.3390/su15118614.

British Standards Institution (BSI), 2011. Sustainability of Construction Works. Methodology for the Assessment of Performance of Buildings: Part 1. Environ. Perform.: BS EN 15978-1 [online] available at: <Retrieved 12/10/2023> www.BSIgroup.com.

British Standards Institution (BSI), 2019. Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products (+A2:2019). Incorporating corrigendum February 2014) [online] available at: <Retrieved 26/06/2024> www.BSIgroup.com.

Cabeza, L.F., Boquera, L., Chàfer, M., Vérez, D., 2021. Embodied energy and embodied carbon of structural building materials: worldwide progress and barriers through literature map analysis. Energy Build. 231, 110612. https://doi.org/10.1016/j.enbuild.2020.110612.

Chastas, P., Theodosiou, T., Kontoleon, K.J., Bikas, D., 2018. Normalising and assessing carbon emissions in the building sector: a review on the embodied CO2 emissions of residential buildings. Build. Environ. 130, 212–226. https://doi.org/10.1016/j.buildenv.2017.12.032.

Craft, W., Oldfield, P., Reinmuth, G., Hadley, D., Balmforth, S., Nguyen, A., 2024. Towards net-zero embodied carbon: investigating the potential for ambitious embodied carbon reductions in Australian office buildings. Sustain. Cities Soc. 113, 105702. https://doi.org/10.1016/j.scs.2024.105702.

Decorte, Y., Van Den Bossche, N., Steeman, M., 2023. Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction. Int. J. Life Cycle Assess. 28 (2), 111–130. https://doi.org/10.1007/s11367-022-02114-0.

Delnavaz, M., Norouzianpour, M., Delnavaz, A., Amiri, S., 2023. A comparative study on the environmental impact of cast in situ concrete and industrialized building systems: a life cycle assessment approach. Environ. Dev. Sustain. 1–19. https://doi.org/10.1007/s10668-023-03738-4.

Densley Tingley, D., Giesekam, J., Cooper-Searle, S., 2018. Applying circular economic principles to reduce embodied carbon. Embod. Carb. Build.: Measur. Manag. Mitigat. 265–285. https://doi.org/10.1007/978-3-319-72796-7_12.

Dixit, M.K., 2017. Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters. Renew. Sustain. Energy Rev. 79, 390–413. https://doi.org/10.1016/j.rser.2017.05.051.

Eberhardt, L.C.M., Birkved, M., Birgisdottir, H., 2022. Building design and construction strategies for a circular economy. Architect. Eng. Des. Manag. 18 (2), 93–113. https://doi.org/10.1080/17452007.2020.1781588.

Ellen MacArthur Foundation (EMF), 2015. Circularity Indicators: an Approach to Measuring Circularity.

Ellen Macarthur Foundation (EMF), 2021. Completing the Picture: How the Circular Economy Tackles Climate Change. Available at: www.ellenmacarthurfoundation.org.

Ellen MacArthur Foundation (EMF) and Arup, 2024. Circular Building Toolkit [Online] Available at: https://ce-toolkit.dhub.arup.com.

Forsythe, P., Wilkinson, S., 2015. Measuring office fit-out changes to determine recurring embodied energy in building life cycle assessment. Facilities 33 (3/4), 262–274. https://doi.org/10.1108/F-08-2013-0065.

Girotto, C.D., Piadeh, F., Bkhtiari, V., Behzadian, K., Chen, A.S., Campos, L.C., Zolgharni, M., 2023. A critical review of digital technology innovations for early warning of water-related disease outbreaks associated with climatic hazards. Int. J. Disaster Risk Reduct., 104151. https://doi.org/10.1016/j.ijdrr.2023.104151.

Grazieschi, G., Asdrubali, F., Thomas, G., 2021. Embodied energy and carbon of building insulating materials: a critical review. Cleaner Environ. Syst. 2, 100032. https://doi.org/10.1016/j.cesys.2021.100032.
Hafez, F.S., Sa'di, B., Safa-Gamal, M., Taufiq-Yap, Y.H., Alrifaey, M., Seyedmahmoudian, M., Stojcevski, A., Horan, B., Mekhilef, S., 2023. Energy efficiency in sustainable buildings: a systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research. Energy Strategy Rev. 45, 101013. https://doi.org/10.1016/j.esr.2022.101013.
Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., Bilec, M.M., 2019. Comparative whole-building life cycle assessment of renovation and new construction. Build. Environ. 161, 106218. https://doi.org/10.1016/j.buildenv.2019.106218.
Hu, M., 2023. A look at residential building stock in the United States - mapping life cycle embodied carbon emissions and other environmental impact. Sustain. Cities Soc. 89, 104333. https://doi.org/10.1016/j.scs.2022.104333.
Illankoon, C., Vithanage, S.C., Pilanawithana, N.M., 2023. Embodied carbon in Australian residential houses: a preliminary Study. Buildings 13 (10), 2559. https://doi.org/10.3390/buildings13102559.
Iran Ministry of Roads and Urban Development (IMRU), 2016. Regulations code 2800 on building design against earthquakes. In: Persian, fourth ed.
Iran Ministry of Roads and Urban Development (IMRU), 2020. National building regulations, class 9: design and construction of reinforced concrete buildings. In: Persian, fifth ed.
Izaola, B., Akizu-Gardoki, O., Oregi, X., 2023. Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. Sustain. Prod. Consum. 40, 252–264. https://doi.org/10.1016/j.spc.2023.07.001.
Jalali, S., Parapari, D.M., Mahdavinejad, M.J., 2019. Analysis of building facade materials usage pattern in Tehran. Adv. Eng. Forum 31, 46–62. https://doi.org/10.4028/www.scientific.net/AEF.31.46.
Joensuu, T., Leino, R., Heinonen, J., Saari, A., 2022. Developing buildings' life cycle assessment in circular economy-comparing methods for assessing carbon footprint of reusable components. Sustain. Cities Soc. 77, 103499. https://doi.org/10.1016/j.scs.2021.103499.
Keena, N., Rondinel-Oviedo, D.R., De-los-Ríos, A.A., Sarmiento-Pastor, J., Lira-Chirif, A., Raugei, M., Dyson, A., 2023. Implications of circular strategies on energy, water, and GHG emissions in housing of the global North and Global South. Clean. Eng. Technol. 17, 100684. https://doi.org/10.1016/j.clet.2023.100684.
Khoshand, A., Khanlari, K., Abbasianjahromi, H., Zoghi, M., 2020. Construction and demolition waste management: Fuzzy analytic hierarchy process approach. Waste Manag. Res. 38 (7), 773–782. https://doi.org/10.1177/0734242X20910468.
Kiessé, T.S., Ventura, A., van Der Werf, H.M.G., Cazacliu, B., Idir, R., 2017. Introducing economic actors and their possibilities for action in LCA using sensitivity analysis: application to hemp-based insulation products for building applications. J. Clean. Prod. 142, 3905–3916. https://doi.org/10.1016/j.jclepro.2016.10.069.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Konietzko, J., Bocken, N., Hultink, E.J., 2020. Circular ecosystem innovation: an initial set of principles. J. Clean. Prod. 253, 119942. https://doi.org/10.1016/j.jclepro.2019.119942.
Lei, B., Yang, W., Yan, Y., Zaland, S., Tang, Z., Dong, W., 2023. Carbon-saving benefits of various end-of-life strategies for different types of building structures. Develop. Built Environ. 16, 100264. https://doi.org/10.1016/j.dibe.2023.100264.
Long, Y., Song, Q., Huang, B., Zeng, X., Wu, H., 2024. Characterizing temporal and spatial characteristics of urban building material metabolism and embodied carbon emissions through a 4D GIS-MFA-LCA model. Resour. Conserv. Recycl. 206, 107642. https://doi.org/10.1016/j.resconrec.2024.107642.
Lu, M., Luo, Z., Cang, Y., Zhang, N., Yang, L., 2024. Methods for calculating building-embodied carbon emissions for the whole design process. Fund. Res. https://doi.org/10.1016/j.fmre.2022.07.015.
Luo, X.J., 2022. Retrofitting existing office buildings towards life-cycle net-zero energy and carbon. Sustain. Cities Soc. 83, 103956. https://doi.org/10.1016/j.scs.2022.103956.
Manfredi, S., Allacker, K., Pelletier, N., Chomkhamsri, K., de Souza, D.M., 2012. Product environmental footprint (PEF) guide [Online] Available at: https://eplca.jrc.ec.europa.eu/%3cRetrieved05/05/2025%3e.
Marsh, A.T.M., Velenturf, A.P.M., Bernal, S.A., 2022. Circular economy strategies for concrete: implementation and integration. J. Clean. Prod. 362, 132486. https://doi.org/10.1016/j.jclepro.2022.132486.
Mirzaie, S., Thuring, M., Allacker, K., 2020. End-of-life modelling of buildings to support more informed decisions towards achieving circular economy targets. Int. J. Life Cycle Assess. 25, 2122–2139. https://doi.org/10.1007/s11367-020-01807-8.
Muñoz, S., Hosseini, M.R., Crawford, R.H., 2023. Exploring the environmental assessment of circular economy in the construction industry: a scoping review. Sustain. Prod. Consum. https://doi.org/10.1016/j.spc.2023.09.022.
Myint, N.N., Shafique, M., 2024. Embodied carbon emissions of buildings: taking a step towards net zero buildings. Case Stud. Constr. Mater. 20, e03024. https://doi.org/10.1016/j.cscm.2024.e03024.
Nawarathna, A., Alwan, Z., Gledson, B., Fernando, N., 2021. Embodied carbon in commercial office buildings: lessons learned from Sri Lanka. J. Build. Eng. 42, 102441. https://doi.org/10.1016/j.jobe.2021.102441.
Oladazimi, A., Mansour, S., Hosseinijou, S.A., 2020. Comparative life cycle assessment of steel and concrete construction frames: a case study of two residential buildings in Iran. Buildings 10 (3), 54. https://doi.org/10.3390/buildings10030054.
Omar, W.M.S.W., Doh, J.-H., Panuwatwanich, K., Miller, D., 2014. Assessment of the embodied carbon in precast concrete wall panels using a hybrid life cycle assessment approach in Malaysia. Sustain. Cities Soc. 10, 101–111. https://doi.org/10.1016/j.scs.2013.06.002.
OneClickLCA, 2024a. How we work with data [Online] Available at: https://oneclicklca.com/en/resources/articles/how-we-work-with-data.
OneClickLCA, 2024b. EPD pre-verification: what is it and how does it work? [Online] Available at: https://oneclicklca.com/en/resources/articles/what-is-epd-pre-verification.
Pasanen, P., Sipari, A., Terranova, E., Castro, R., Bruce-Hyrkas, T., 2018. The embodied carbon review—embodied carbon reduction 100+ regulations and rating systems globally - bionova ltd [Online] Available at: https://www.buildingtransparency.org.
Pedersen, E., Remmen, A., 2022. Challenges with product environmental footprint: a systematic review. Int. J. Life Cycle Assess. 27, 342–352. https://doi.org/10.1007/s11367-022-02022-3.
Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A., 2017. Circular economy: measuring innovation in the product chain. Planbureau Voor de Leefomgeving 2544.
Seyedabadi, M.R., Abolhassani, S.S., Eicker, U., 2023. District cradle to grave LCA including the development of a localized embodied carbon database and a detailed end-of-life carbon emission workflow. J. Build. Eng. 76, 107101. https://doi.org/10.1016/j.jobe.2023.107101.
Temizel-Sekeryan, S., Rios, F.C., Geremicca, F., Bilec, M.M., 2023. Circular design and embodied carbon in living buildings: the missing potential. J. Architect. Eng. 29 (3), 04023013. https://doi.org/10.1061/JAEIED.AEENG-1445.
Wang, X., Huang, B., Wang, Y., Liu, J., Long, Y., Daigo, I., 2023. The impact of allocation methods on carbon benefits-a case study of construction waste recycling. Resour. Conserv. Recycl. 199, 107269. https://doi.org/10.1016/j.resconrec.2023.107269.
Waldman, B., Huang, M., Simonen, K., 2020. Embodied carbon in construction materials: a framework for quantifying data quality in EPDs. Build. cities 1 (1). https://journal-buildingscities.org/articles/10.5334/bc.31.
Wiedenhofer, D., Schug, F., Gauch, H., Lanau, M., Drewniok, M.P., Baumgart, A., Virág, D., Watt, H., Serrenho, A.C., Tingley, D.D., 2024. Mapping material stocks of buildings and mobility infrastructure in the United Kingdom and the Republic of Ireland. Resour. Conserv. Recycl. 206, 107630. https://doi.org/10.1016/j.resconrec.2024.107630.
World Business Council for Sustainable Development (WBCSD), 2022. Circular Transition Indicators V4.0: Metrics by Business. by business [Online] Available at: www.wbcsd.org.
World Green Building Council (World GBC), 2019. Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon, pp. 7–14 [Online] Available at: www.worldgbc.org.
Zakerhosseini, A., Abdoli, M.A., Molayzahedi, S.M., Salmi, F.K., 2023. Life cycle assessment of construction and demolition waste management: a case study of Mashhad, Iran. Environ. Dev. Sustain. 1–27. https://doi.org/10.1007/s10668-023-03703-1.