

REVIEW

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Life cycle costing in the circular economy: a state-of-the-art review of current trends in the building construction sector

Annabel Vella^{1,2*}, Haitham Abu-Ghaida^{2,3}, Wai Chung Lam^{1,2} and Michiel Ritzen^{1,2}

*Correspondence:

Annabel Vella
annabel.vella@vito.be
¹VITO, Mol, Belgium
²EnergyVille, Genk, Belgium
³Hasselt University, Hasselt, Belgium

Abstract

The building construction sector's resource intensity and linear practices demand transition to a Circular Economy (CE). Life Cycle Costing (LCC) offers a means to quantify the long-term financial implications of circular approaches, yet its application in the context of CE within building construction remains underexplored and methodologically fragmented. This paper comprehensively reviews the application of LCC in promoting CE principles within the building construction sector. Through a structured review of 51 case studies from published literature, this study identifies current practices, methodological variations, and gaps in integrating LCC with CE principles. The findings reveal a slow but increasing trend in using LCC to evaluate the economic feasibility of CE strategies in the building construction sector. While financial LCC remains dominant, other approaches include environmental LCC, which incorporates carbon and landfill costs, and social LCC, which considers broader social impacts, particularly in waste management and production processes. However, challenges persist, primarily the linear progression of building life cycle stages assumed in LCC, which limits its application in the CE, compounded by the lack of a standardised LCC methodology. This is evident in the diverse types of LCC used, the definition of system boundaries, and the consideration of cost perspectives. The study highlights the potential of LCC to facilitate circularity in the building construction sector by integrating economic, social, and environmental dimensions, providing insights for researchers and practitioners to enhance the implementation of robust LCC frameworks.

Keywords LCC, Life cycle cost, Circular economy, Building, Construction, Literature review

1 Introduction

1.1 Environmental and economic impacts of the building construction sector

The construction sector places significant pressure on global resources, ecosystems, and the climate, accounting for the largest share of raw material consumption worldwide [1]. Its material demand is projected to nearly double by 2060 [2], dominated by non-metallic minerals such as sand, gravel, and limestone, while metals, though used in smaller



quantities, cause high environmental burdens to their polluting extraction and processing methods [2].

Furthermore, embodied energy from materials like concrete, steel, and aluminium accounts for about 5% of the global final energy consumption, while operational energy brings buildings' total share to around 30% [3]. The sector also contributes heavily to waste generation, as an estimated 35% of construction, renovation, and demolition waste ends up in landfills largely through linear production and disposal practices [4].

Despite these impacts, the construction sector plays a vital role in global economic development, contributing to around 6% of the global gross domestic product (GDP) and employing around 100 million people [1]. However, its scale, complexity, and interdependence with other sectors hinder the adoption of life cycle perspectives and integrated sustainability strategies [5]. As urbanisation and wealth accelerate construction demand [6], these systemic inefficiencies highlight the need for approaches that align economic performance with environmental responsibility.

1.2 Transitioning building construction to a circular economy

The Circular Economy (CE) offers a promising alternative to address these challenges by retaining material value and minimising waste. Defined by the Ellen MacArthur Foundation [7], CE replaces the traditional 'end-of-life' concept with strategies of reuse, repair, and recycling. Applied to buildings, it promotes design for adaptability, disassembly, and material recovery, thereby extending asset life and reducing embodied impacts [8].

However, translating CE principles into practice remains constrained by economic and institutional barriers [9–12]. Short investment horizons, limited access to finance, and the low cost of virgin materials reduce incentives for circular solutions.

1.3 Life cycle costing as a tool to evaluate the circularity in building construction

Addressing the challenges outlined above highlights the importance of evaluating the economic feasibility of circular strategies across the entire building life cycle [13]. In the context of buildings, Life Cycle Costing (LCC) provides a structured approach to quantify costs from cradle to grave, encompassing construction, operation, and end-of-life phases [14]. Standardised methods, such as EN 16627:2015 [15], ISO 1568:2017 [16], and Level(s) indicator [17], define the system boundaries (Modules A–C) and allow inclusion of potential revenues from recovered materials beyond the system boundary (Module D). While these frameworks apply to new construction, retrofitting, and renovation, their inherently linear progression of life stages limits compatibility with the regenerative principles of the CE [18, 19].

To evaluate CE strategies more comprehensively, authors increasingly call for methods integrating environmental, social, and economic dimensions [20]. This is evidenced by the various studies where LCC complements environmental Life Cycle Assessment (LCA) [21, 22]. Beyond the conventional financial LCC (fLCC) that examines direct monetary costs, the tool can be expanded to include broader environmental and social impacts in environmental LCC (eLCC), full environmental LCC (feLCC), or social LCC (sLCC) [16, 23, 24].

Recent research reflects growing efforts to connect life-cycle-based assessment methods with CE principles in construction. Literature reviews by Norouzi et al. [25] and Lovrenčić Butković et al. [21] show that studies on circularity largely concentrate

on waste management, material reuse, and environmental performance, where LCA remains dominant. Similarly, Buyle et al. [26] provided one of the earliest comprehensive reviews of LCA in construction, but giving limited consideration to economic assessment.

Parallel to this environmental emphasis, a separate line of research has examined the development and application of LCC within the construction sector. Emekci [27] presented a state-of-the-art review that traced the evolution of LCC from cost-in-use analyses to broader life-cycle evaluations, highlighting its potential for economic decision support while noting limited integration with sustainability and circularity principles. Manewa et al. [28] identified a post-2013 surge in LCC research and a shift toward coupling it with LCA and performance optimisation. Complementing this, AlJaber et al. [9] explored how digitalisation and Building Information Modelling (BIM) can enhance LCC application by improving cost transparency and enabling circular design.

Moving toward holistic perspective, Larsen et al. [14] explored the integration of LCA, LCC, and social LCA (S-LCA) within a life cycle sustainability assessment (LCSA) framework, noting that current applications remain fragmented and largely conceptual. Broader reviews of CE assessment tools at the micro level [29] similarly reveal that few frameworks simultaneously address environmental, economic, and social dimensions.

Although various reviews have examined circularity in buildings and life-cycle assessment approaches, to the authors' knowledge, none has yet provided a state-of-the-art synthesis that jointly addresses LCC, CE principles, and building construction. Existing literature reviews typically focus either on circular design and material recovery within CE frameworks or on methodological developments in life-cycle assessment, mainly LCA, and to a lesser extent LCC.

1.4 Aims and objectives of the research

The present paper therefore fills this clear research gap by offering the first comprehensive state-of-the-art review of how LCC is applied within the circular construction of buildings. It systematically examines methodological developments, practical applications, and emerging trends that connect LCC to circular principles in the building sector. This is essential to understand how economic evaluation through LCC can support the implementation of circular strategies in buildings, identify methodological synergies and inconsistencies, and provide a unified knowledge base to guide both research and practice in sustainable construction.

2 Methods

2.1 Research questions and steps

This paper presents a systematic literature review of peer-reviewed publications, focusing on case studies evaluating CE strategies in the building construction sector using LCC. This comprehensive analysis aims to provide researchers and practitioners with a clear understanding of the current landscape and future directions in this field. The research addresses the questions below:

- Which life cycle stages are targeted for circularity, and what types of CE strategies are implemented in case studies?
- What are the goals of using LCC to evaluate circularity?
- Which types of LCC are applied to assess CE strategies in building construction?

- How are system boundaries defined in the case studies, and to what extent are costs and benefits beyond the building or product life cycle included?
- What are the knowledge gaps and uncertainties in conducting LCC within the CE of building construction?

Inspired by Z. Liu & Kringos [30], the four-step framework below was used to identify and evaluate references for inclusion based on the research questions.

- Collection of references: defining and setting eligibility criteria for selecting references.
- Conducting quantitative analysis: using quantitative methods to analyse characteristics of collected references, such as publication numbers and the temporal and geographical distribution of case studies.
- Development of reviewing framework: developing a review framework with descriptive and analytical attributes for evaluating selected references.
- Review of references: review selected references using the review framework to address the research questions.

2.2 Collection of references

The literature search was designed to systematically identify peer-reviewed studies that examine the application of Life Cycle Costing (LCC) within the context of Circular Economy (CE) in the building construction sector. The Scopus database was selected as the primary search database due to its extensive multidisciplinary coverage with strong representation of journals in engineering, construction, and sustainability fields that are central to this research. It also has robust search functionalities that support complex Boolean operators. This choice is supported by comparative bibliometric analyses showing that Scopus and Web of Science (WoS), two comparable multidisciplinary citation databases, exhibit around 90–95% overlap in indexed publications, with Scopus offering broader coverage in applied and technical disciplines relevant to the built environment [31–33]. To further ensure comprehensiveness of the search, Google Scholar was consulted as supplementary source for backward citation snowballing for screening reference lists of selected studies, to capture additional empirical research not explicitly indexed under the search string adopted.

In the first step of the references collection process (Fig. 1), a structured Boolean query was developed around four concept groups: (1) LCC, (2) building construction, (3) circularity principles, and (4) empirical evidence. The query was developed through an iterative process and testing various combinations to ensure all relevant terms were captured. The final search string combined four key concept groups:

- LCC terms (“LCC” OR “Life Cycle Cost”) to capture both abbreviated and full terminology variations,
- Building construction sector terms (“building” OR “construction” OR “built environment” OR “construction sector”) to encompass the broader built environment while maintaining focus on buildings,
- Circularity-related terms (“circular” OR “circular economy” OR “reuse” OR “recycl*” OR “adapt*” OR “refurbish”) to include both explicit circular economy references and related concepts, and.

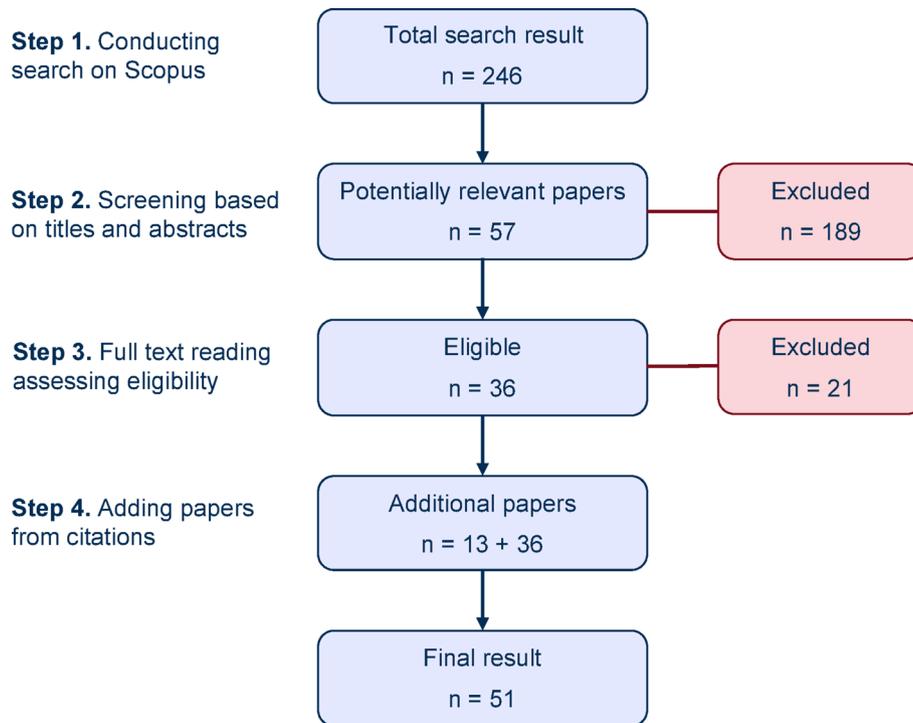


Fig. 1 Literature search and screening methodology

- Empirical research indicators (“case stud*” OR “empirical” OR “application”) to focus on practical applications rather than theoretical frameworks.

The search was restricted to peer-reviewed articles and book chapters to ensure scientific rigor, and was limited to English language publications to maintain consistency in screening and analysis. The search yielded 246 potentially relevant references.

Following PRISMA guidelines [34], in the second step of the process, all 246 records retrieved from Scopus were screened by title and abstract against predetermined inclusion criteria. Studies were included if they:

- Applied LCC as an analytical method, not just as a mentioned concept,
- Explicitly addressed CE principles in building construction, demonstrating clear links between LCC and circularity,
- Presented empirical data or case study findings rather than purely theoretical discussions,
- Focused specifically on building construction, excluding infrastructure and civil engineering applications, and.
- Demonstrated CE strategies in at least one of the building life cycle stages.

This screening process resulted in 57 peer-reviewed references.

In the third step, these remaining papers were assessed in full text for eligibility following the same criteria above. To ensure rigor and minimise bias, the screening process in this step was documented using a standardised form where the final decision was recorded along with detailed notes justifying each decision. Thirty-six out of 246 papers were found relevant to the topic.

The fourth step in the process involved systematic backward citation snowballing using Google Scholar. Reference lists of the 36 included papers were reviewed, and

relevant papers were screened using the same inclusion criteria, first based on title and abstract and then based on full text review. This step increased the number by 13 papers. Ultimately, 51 papers were deemed relevant for this review. The search and screening process is illustrated in Fig. 1.

2.3 The review framework

A review framework was developed to collect data from the selected references to address the research questions. It focused on understanding how LCC is used to evaluate CE strategies in building construction case studies, utilising a framework with 13 attributes, grouped as follows:

- Overview of literature landscape: (1) publication journal, (2) year of publication, and (3) country of case study.
- Descriptive attributes of case studies: (4) life cycle stage(s) targeted for circularity, (5) types of CE strategies, and (6) applications of CE strategies.
- Methodological attributes of LCC: (7) types of LCC employed (fLCC, eLCC, feLCC, or sLCC), (8) system boundaries, (9) the consideration of benefits beyond life cycle, (10) cost perspective(s), (11) goal of the LCC, and (12) other tools used in conjunction with LCC.
- Methodological gaps and barriers: (13) identified gaps and barriers in LCC methodology.

3 Results and discussion

The following sections present the outcomes of the case study analysis of the 51 selected papers. The results are discussed according to the four groups of attributes within the review framework, with the final section focusing on four case studies to provide a more detailed illustration of how LCC is utilised to assess CE strategies in building construction.

3.1 Overview of literature landscape

An analysis of the general attributes of the 51 selected case studies is depicted in Figs. 2, 3 and 4. These figures illustrate the overall trends of studies related to the topic in terms of publication journals, and the temporal and geographical distribution of case studies.

All the selected references are peer-reviewed academic papers. The 51 papers are published in 28 different journals, with three journals being more prevalent: Journal of

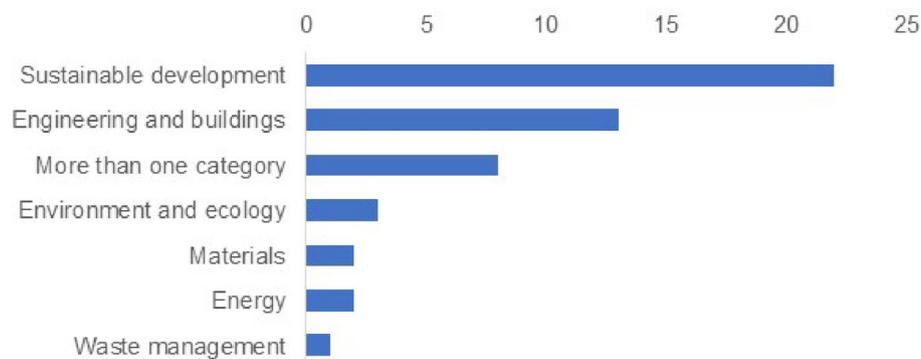


Fig. 2 The distribution of studies by the primary topic of the publication journal where they are featured

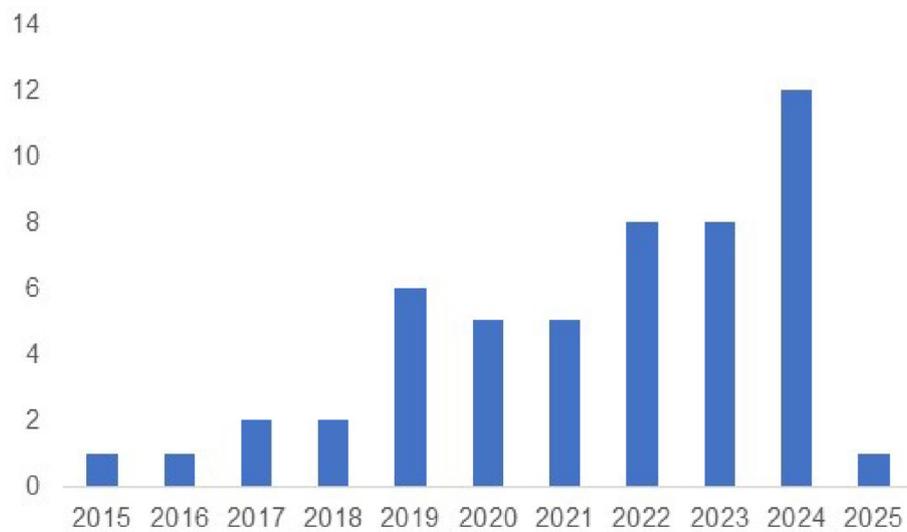


Fig. 3 The distribution of studies by publication year

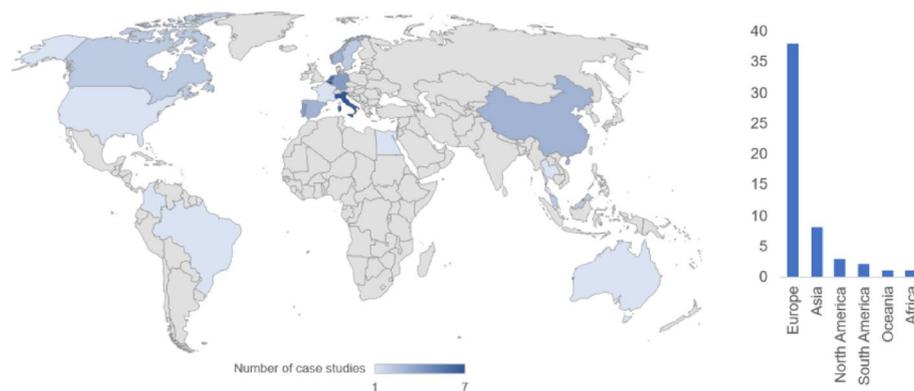


Fig. 4 The distribution of case studies by country (left) and continent (right)

Cleaner Production (9 papers), Sustainability (9 papers), and *Journal of Building Engineering* (6 papers). Interestingly, when grouping the journals by their primary topic domain (Fig. 2), the largest share of case studies is published in journals focusing on sustainable development, represented by 25 instances (41%). Seventeen case studies (28%) are published in engineering and buildings journals. Other journal categories capture between one to three case studies (environment and ecology, materials, energy, waste management, and life cycle assessment), and nine studies are published in journals with overlapping topics.

As illustrated in Fig. 3, the integration of LCC with CE principles in building construction research has emerged predominantly in the last decade. The growth in this area has been gradual but slow. Up to 2018, there were between one and two publications per year, followed by an increase in publications ranging from five to eight per year until 2023. The peak in the number of publications occurred in 2024 with 12 publications.

The chart on the right side of Fig. 4 shows that the largest share of case studies (38) is applied in European countries, with Belgium (7), Italy (7), and the Netherlands (6) being the most represented. Fifteen case studies are applied outside Europe, with Asia (8) being the most represented.

3.2 Descriptive attributes of case studies

The literature demonstrates a strong relationship between the life cycle stages targeted for circularity and the type and application of CE strategies (Table 1). The studies reviewed cover various stages, including product or material manufacturing, construction, maintenance and/or repairs, renovation and/or retrofitting, and end of life. The CE strategies can be categorised into the following seven groups: (1) material/product reuse, (2) use of secondary material, (3) recycling processes, and (4) recovery potential at end of life. Additionally, various CE strategies serve as a means to extend the life of building elements or the building itself. These include (5) demountable and/or adaptable solutions, (6) maintenance and repairs, and (7) refurbishment and regeneration, which serve to delay deconstruction.

Manufacturing-focused solutions (nine studies) predominantly involve secondary material use, aimed at reducing virgin, non-renewable raw material consumption during production, of which analyse concrete mixes with recycled material [35, 36], use of polymeric waste in ceiling tiles [37], lime-based plasters with upcycled materials [38], and hemp fibre insulation material [39]. One study extends the impact beyond manufacturing to increase circularity during construction, through structural trusses made from recycled cardboard waste [40]. Other studies extend the impact from manufacturing to the end-of-life stage (three studies), where recovery potential is also assessed. Such studies examine circular façade and circular kitchen solutions [19], building insulation materials from waste [41], and recycled construction and demolition waste materials in a prefabricated concrete façade [42].

At the construction stage (10 studies), CE strategies emphasise secondary material use, reuse, recovery potential. Studies focused implemented CE strategies to target the construction stage address recycled carbon-reinforced concrete floors [43], reused steel beams [44], waste-based façades [45], formwork designed to increase reuse cycles [46], and concrete mixes with recycled materials [47]. Two construction solutions target enhanced durability to reduce maintenance needs, such as concrete mixes with waste material [48, 49]. Similar to circularity in manufacturing, three studies extend the impact beyond the construction stage to increase circularity at end of life through recovery potential. This includes studies that examine concrete mixes comprising waste material [13, 50], and shipping containers repurposed as modular housing units [51].

The integration of circularity at the maintenance and repair stage is analysed in fewer studies (three), typically focusing on retrofitting needs and life extension through optimised maintenance planning systems [52], repair techniques for concrete balconies [53], and self-healing concrete to reduce maintenance needs [54].

Renovation and retrofitting emerge as a critical stage for circularity, with 15 studies targeting this stage. Various solutions aim to reduce environmental impacts during renovation through demountability and adaptability. These include an adaptive façade [55], a circular kitchen [20], an expandable house [56], reversible and demountable wall systems [22, 57, 58], deep building envelope renovation designed for disassembly [59], and demountable building elements designed for future reuse [60]. Other studies focus on optimising renovation strategies [61], or applying renovation as a means to extend the building lifespan [62], as well as assessing renovation in relation to demolition and reconstruction [63, 64]. Some strategies aim to reduce resource impacts during renovation through reused and secondary material, such as reused ductwork [65], recycled

cork aggregate in mortar [66], and recycled construction waste in prefabricated concrete panels [67].

Case studies targeting mainly circularity at the end-of-life stage also dominate the relevant literature, with a total of 14 studies. Various studies consider end-of-life recovery potential at the design or construction stage to optimise reuse and recycling in the future. A wide range of solutions is explored, including construction systems to optimise recyclability and reuse potential [68], building glass façade frames [69], a building integrated photovoltaics façade [70], timber building systems [71, 72], solar cell envelope system [73], and expanded polystyrene (EPS) insulation beads and boards [74]. Additionally, studies focusing on this stage assess demolition waste management approaches aimed at improving recyclability and reuse [75, 76], and compare downcycling with recycling of aggregates [77]. Other studies extend end-of-life strategies to manufacturing and construction in the next building life cycle, demonstrating how materials salvaged from deconstructed buildings can be reintegrated into new projects. This includes the use of recycled sand in mortars [78], laminated timber from recycled wood [79], and the reuse of structural steel [80]. Another study takes a wider approach by optimising urban block-scale demolition and reconstruction based on CE principles [81].

3.3 Methodological attributes of LCC

3.3.1 Types of LCC, system boundaries, and cost perspectives

The methodological approach employed in LCC varies notably across the case studies, primarily in three aspects: (1) the type of LCC used, (2) the definition of system boundaries, and (3) the cost perspective. Each of these aspects influences the scope and type of costs considered in the study.

The reviewed studies are classified into four main types of LCC: (1) fLCC, which assesses direct monetary costs, (2) eLCC, which internalises environmental costs such as landfill or carbon taxes, (3) feLCC, encompassing both internalised and externalised environmental costs, and (4) sLCC, which monetises costs and benefits from a broader societal perspective [23, 24]. In the reviewed studies, the type of LCC employed was not always explicitly stated. In such cases, they were inferred from the description of cost and benefit components, and considered stakeholder perspectives.

As presented in Fig. 5, the fLCC emerged as the predominant form of LCC, appearing in 28 (55%) of the case studies [13, 19, 20, 22, 37, 39, 43, 45–49, 52–54, 56–58, 60, 62, 63, 65–67, 71–74], regardless of the implementation stage of the CE strategies. This encompassed the direct financial expenses incurred by the stakeholders. eLCC, adopted in 14 studies (27%) [36, 38, 40–42, 44, 59, 68, 69, 75, 77–79, 81], was most commonly adopted in cases targeting circularity in the manufacturing, construction, renovation or retrofitting, and end-of-life stages. The eLCC accounted for internalised environmental costs, mainly carbon and landfill. Four case studies extended the analysis to include externalised environmental costs in the adopted feLCC [35, 51, 55, 61]. The social costs associated with carbon and air pollutants addressed through sLCC were observed in five case studies [50, 64, 70, 76, 80]. The case conducted by Tanthanawiwat et al. [76] adopted a holistic sLCC approach by considering the direct costs of construction and demolition waste management and the externalised costs of each environmental impact category identified in the LCA.

Table 1 The life cycle stages targeted for circularity in the case studies, the type of CE strategies and application of CE strategies (with country of application in brackets)

Life cycle stage(s) targeted for circularity	Count of studies	Type of CE strategies	Applications of CE strategies (and country)	References
Manufacturing	5	Secondary material	Lightweight recycled aggregates in concrete mixtures (Italy); Ceiling tiles with polymeric waste (Spain); Lime-based plasters with upcycled materials (Germany); Concrete and mortar mixes with recycled construction waste and biomass ash (Spain); Hemp fibre insulation material (Sweden)	[35–39]
Manufacturing and construction	1	Secondary material	Structural trusses made from recycled cardboard waste (Australia)	[40]
Manufacturing, renovation/retrofitting, and end of life	1	Secondary material; Demountable/Adaptability; Recovery potential	Circular façade and circular kitchen (Netherlands)	[19]
Manufacturing, and end of life	2	Secondary material; Recovery potential	Building insulation material from waste (China); Recycled construction and demolition waste materials in prefabricated concrete façade (Netherlands)	[41, 42]
Construction	5	Reuse; Secondary material; Recovery potential	Recycled carbon-reinforced concrete in floors (Germany); Formwork material for concrete structures (Malaysia); Waste-based façade designs (Spain); Concrete mix with recycled concrete aggregates and fly ash (Portugal); Reused steel beams (Korea)	[43–47]
Construction, and maintenance/repairs	1	Secondary material	Self-healing recycled ultra-high-performance concrete using crushed concrete as aggregate replacement (Italy)	[49]
Construction, maintenance/repairs, and end of life	1	Secondary material; Recovery potential	Reinforced concrete with treated wastewater, recycled concrete aggregates, and fly ash for building construction (Qatar)	[48]
Construction, and end of life	3	Reuse; Recovery potential; Secondary material	Circular material in the structure, skin and space of a building (Netherlands); Eco-concretes using fly ash and blast furnace slag (Colombia); Shipping containers repurposed as modular housing units (Canada)	[13, 50, 51]
Maintenance/repairs, and renovation/retrofitting	1	Maintenance/Repairs	Optimised maintenance planning system (Portugal)	[52]
Maintenance/repairs, and end of life	2	Maintenance/Repairs; Recovery potential	Repair solutions of concrete balconies (Belgium); Self-healing concrete in a wall construction (Italy)	[53, 54]
Renovation/retrofitting	7	Reuse; Secondary material; Demountable/Adaptability; Refurbishment/Regeneration	Reuse of ductwork in retrofitting (Belgium); Optimised building regeneration strategy (China); Energy-efficient renovation strategies to extend building life (Norway); Adaptive facade system (Germany); Mortar made with recycled cork aggregate (Portugal); Recycled construction waste in prefabricated concrete panels (Netherlands); Structural refurbishment versus demolition and reconstruction (Portugal)	[55, 61–63, 65–67]

Table 1 (continued)

Life cycle stage(s) targeted for circularity	Count of studies	Type of CE strategies	Applications of CE strategies (and country)	References
Renovation/retrofitting, and end of life	8	Reuse; Secondary material; Demountable/Adaptability; Refurbishment/Regeneration; Recovery potential	Demountable internal wall assemblies (Belgium); Circular kitchen (Netherlands); Expandable house (Belgium); Reversible wall partitioning systems (Belgium); Deep building envelope renovation designed for disassembly (Italy); Building renovation versus new building (Sweden); Modular steel wall panel system (Brazil); Demountable building elements designed for future reuse (Belgium)	[20, 22], 56–64]
End of life	10	Recycling; Recovery potential	Building glass façade frames to increase recyclability and reusability (Italy); Downcycling versus recycling of aggregates (Belgium); Recovery solution of demolition waste (China); Building integrated photovoltaics façade (Norway); Recovery potential of timber wall and floor panelling (Malaysia); Deconstructed EPS insulation beads and boards (Switzerland); Demolition waste management solutions (Thailand); Recovery potential of timber building system (USA); Recyclable solar cell envelope system (Norway, Netherlands, and Italy); Construction systems optimising recyclability and reuse potential (Egypt)	[68–77]
End of life; manufacturing	2	Recycling; Secondary material; Recovery potential	Recycled sand from leftover concrete for use in dry industrial mortars (France); Laminated timber from recycled solid wood from construction (Germany)	[78, 79]
End of life; construction	2	Reuse; Secondary material; Demountable/Adaptability; Recovery potential	Reuse of structural steel (Canada); Urban block scale demolition and reconstruction with circular economy principles (Italy)	[80, 81]

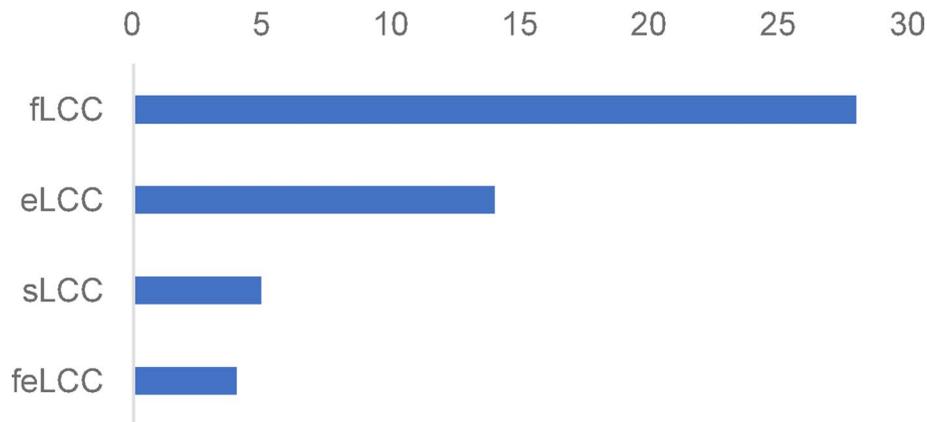


Fig. 5 The number of case studies by type of LCC

Table 2 LCC methodological details of the case studies along (with number of studies in brackets)

System boundaries	LCC type	Type of CE strategies	References
Cradle to grave (19)	fLCC (14); eLCC (4); sLCC (1)	Demountable/Adaptability (5); Secondary material (9); Recovery potential (9); Recycling (2); Reuse (2)	[19, 20, 22], 37– [39, 42], 45– [47, 49, 50, 54, 57, 69], 72– [74, 81]
Cradle to gate (3)	fLCC (1); eLCC (1); feLCC (1)	Secondary material (3)	[35, 36, 43]
Cradle to construction (2)	eLCC (2)	Reuse (1); Secondary material (1)	[40, 44]
Construction to grave (10)	fLCC (5); eLCC (3); sLCC (2)	Demountable/Adaptability (3); Recovery potential (5); Recycling (1); Refurbishment/Regeneration (1); Reuse (1); Secondary material (4)	[13, 41, 48, 56, 58, 59, 64, 68, 70, 71]
Construction to use (1)	feLCC (1)	Demountable/Adaptability (1)	[55]
Use (6)	fLCC (5); feLCC (1)	Maintenance/Repairs (2); Refurbishment/Regeneration (3); Reuse (1)	[52, 53], 61– [63, 65]
Use to grave (3)	fLCC (3)	Reuse (1); Demountable/Adaptability (1); Recovery potential (1); Secondary material (2)	[60, 66, 67]
End of life (3)	eLCC (2); sLCC (1)	Recycling (2); Recycling (1); Secondary material (1)	[75, 76, 79]
Grave to cradle (1)	eLCC (1)	Secondary material (1); Recovery potential (1)	[78]
Grave to construction (2)	eLCC (1); sLCC (1)	Recycling (1); Reuse (1)	[77, 80]
Grave to grave (1)	feLCC (1)	Reuse (1); Recovery potential (1)	[51]

A summary of the system boundaries applied in the reviewed case studies is presented in Table 2, organised by the type of LCC and corresponding circularity type. The categorisation of the system boundaries in this review follows the life cycle modular framework defined in EN 16627:2015 [15] for life cycle costing. Similar to the type of LCC, the system boundaries were not always explicitly stated in the reviewed studies, and in such cases this was inferred from the cost and benefit components considered.

The system boundaries defined in the case studies vary considerably, with cradle to grave being the most commonly used (19 studies), followed by construction to grave (10 studies) and use stage (six studies). These boundaries are most often associated with fLCC and are conducted in relation to a varied range of circularity types such as reuse, recovery potential, secondary material use, and demountability.

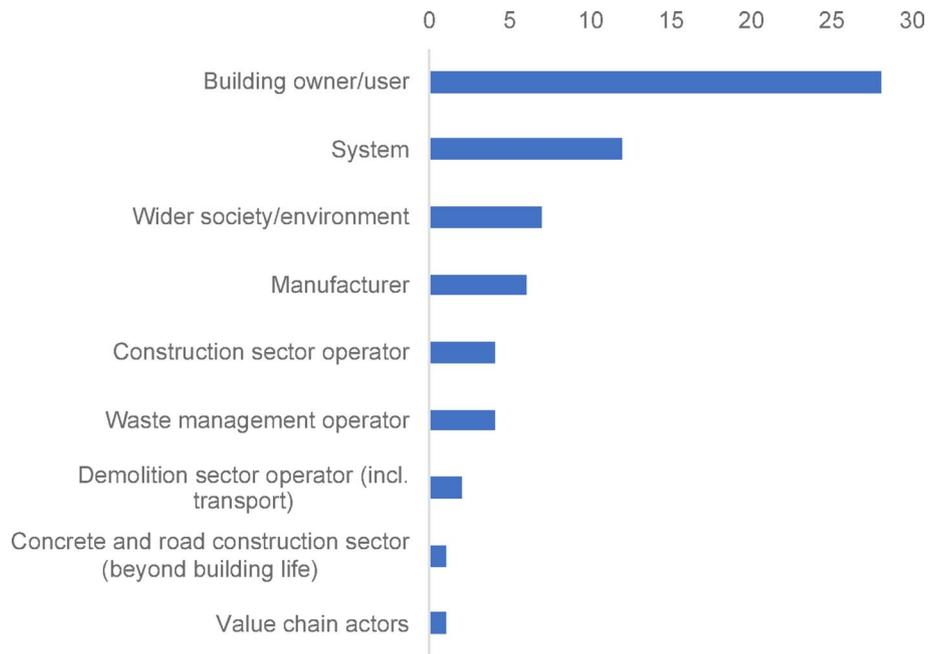


Fig. 6 The representation of different perspectives in the case studies.

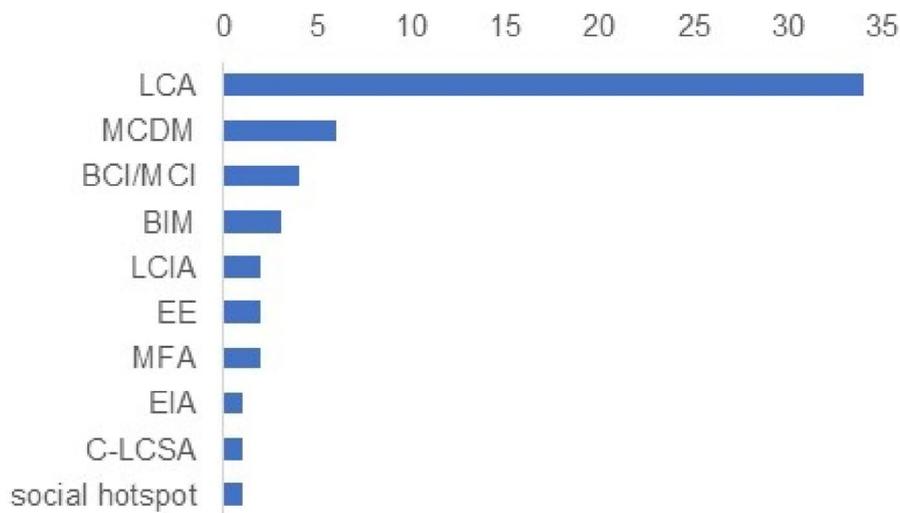


Fig. 7 The number and share of case studies using other tools in conjunction with LCC.

Unconventional or non-linear system boundaries, such as end of life, grave to cradle, grave to construction, and grave to grave, appear less frequently but are noteworthy. These are associated with eLCC, sLCC, and feLCC, and their use is focused on secondary material use, reuse, and recycling.

Most studies incorporate costs associated with the end-of-life stage, except those focusing solely on early stages of production or construction. Nevertheless, the specific end-of-life costs considered in case studies varied, including activities such as demolition and dismantling, transportation to waste management facilities, and waste disposal. The significance of material recovery potential in evaluating CE strategies in buildings is

underscored by the consistent inclusion of waste disposal or recovery costs in almost all pertinent case studies.

In addition to the end-of-life costs and system boundaries observations, 30 (59%) of the case studies considered costs and benefits extending beyond the building life cycle. In most instances, these were factored in as residual value, estimated based on the potential sale value of recovered material or energy. While most case studies assigned the residual value to the building owner, others assigned it to the building system [57, 69], the demolition operator [75], or the recycling plant operator [20, 75]. Another study assigned it to the broader society [70] or as a cost to the user in the next life cycle [77]. Tanthanawiwat et al. [76] adopted a distinct approach by monetising the benefits beyond the building life cycle by accounting for the avoided raw material in the next cycle and assigning this to the broader society.

Regarding the perspective of costs, LCC in the case studies was typically conducted from a single perspective. However, 13 studies adopted a multi-perspective approach, where each perspective was considered separately. As shown in Fig. 6, the most prevalent perspective in all case studies is that of the building owner, considered in 28 studies [13, 19, 22, 39, 41, 42, 44, 45, 48–56, 59–63, 65, 68, 70–72, 80], or building user considered in one study [20]. This was regardless of the stage at which the CE strategies are implemented, following the conventional Total Cost of Ownership (TCO) approach. The perspective of manufacturers was reflected in six case studies [19, 20, 35, 36, 40, 78], and that of construction companies observed in four studies [40, 43, 46, 78]. These focused on the production or construction processes, predominantly evident in CE strategies implemented during the pre- or early stages of the building life cycle. Conversely, the perspective of the demolition sector and the waste management operators, was observed in two [75, 77] and four [20, 75–77] case studies, respectively. These perspectives were commonly noted in studies focused on the end-of-life stages, including demolition activities capturing transportation of waste, and waste management operations including recycling or landfilling. In addition to looking at the waste management operators' perspective, the study conducted by di Maria et al. [77] looked beyond the end of life and waste management stages, considering the perspective of the concrete and road construction operator using the recovered material.

Furthermore, Kulakovskaya et al. [74] conducted research presenting a distinctive approach to evaluate end-of-life options for EPS using the entire Swiss building stock as a case study. The study considered costs and benefits in LCC from a holistic perspective, encompassing the entire value chain, including production, retail, installation, use, demolition, and waste processing. Another 12 case studies were analysed from the system's perspective, conducted from the viewpoint of the installed product, material, or building component. These typically considered cradle-to-grave or construction-to-grave boundaries [37, 38, 47, 57, 58, 64, 69, 73, 81], and to a lesser extent focused on the use phase (renovation/retrofitting) [66, 67], or end-of-life stage capturing the recovery aspect [79].

The wider societal and environmental perspectives were observed in seven case studies, with all of them analysing this perspective in addition to another one; namely with building owner [50, 61, 68, 70, 80], manufacturer [35], or waste management operators [76]. In these cases, the type of LCC was eLCC, feLCC, or sLCC.

3.3.2 Goals of LCC

The literature demonstrates a broad range of goals in relation to the use of LCC to obtain economic insights. The goals of LCC can be grouped into key categories, reflecting how LCC is applied to assess economic implications across the building life cycle. These categories include (1) evaluating the economic viability of CE strategies in building construction compared to conventional approaches, (2) optimising CE strategies, (3) assessing the affordability of CE strategies, (4) evaluating the adequacy of incentives for circularity, and (5) identifying economic drivers for circularity from different stakeholder perspectives.

The primary goal of LCC of 38 case studies is to evaluate the economic performance of CE strategies in buildings, including material use, construction techniques, maintenance, refurbishment, and end-of-life strategies, in terms of their life cycle costs. Typically, this is done by comparing life cycle costs between circular and conventional (linear) strategies to determine whether circularity offers net economic benefits. In these case studies, LCC was used to estimate the economic performance of CE strategies and to showcase their contribution to the CE. This is achieved by comparing the various costs associated with these solutions, which can vary based on the costs of inputs (at initial investment, maintenance, or refurbishment stages), and costs and benefits of outputs (at the end of life due to dismantling alternatives, waste disposal methods, and recovery potential).

LCC is also widely used (in eight studies) to optimise material selection and design strategies by identifying the most cost-effective mix of materials and structural elements. For instance, examples include investigating the optimal mix design of lightweight aggregates [35] and concrete mix [47] for cost and environmental benefits. Other studies find the optimal circularity level in relation to life cycle costs [13, 52, 65], and establish the optimal timing of building regeneration interventions to minimise economic and environmental impacts [61].

In five case studies, the aim of the LCC extends beyond evaluating the economic feasibility of circular options. LCC is used in case studies to identify economic drivers for circularity from different perspectives. In one study, the LCC served as a tool to evaluate the adequacy of the allocated incentives for promoting circular production and consumption [70]. LCC is also used to investigate financial motivations across various stakeholder groups, including developers, policymakers, and end-users, to understand what drives investment in circular building solutions [75], and to explore economic barriers and opportunities for transitioning from downcycling to higher-value recycling processes [77]. LCC is also used to assess the affordability of CE strategies [56], assessing whether expandable houses can provide cost-effective alternatives in the market.

3.3.3 Other tools used in conjunction with LCC

In addition to LCC, several case studies combine LCC with other analytical tools to provide a more comprehensive assessment of circular building solutions. In 39 (76%) case studies, LCC was used with at least one other tool, and in 14 of these studies, LCC was combined with at least two different tools. As illustrated in Fig. 7, the most prevalent combination was LCC and LCA, which enhanced the economic assessment with environmental impact assessment. Other complementing tools included the Building Circularity Indicator (BCI) and Material Circularity Indicator (MCI) [13, 43, 58, 59, 76], and Material (and energy) Flow Analysis (MFA) [19, 74], which were employed to evaluate

the circularity level of alternative solutions. Three studies have integrated LCC with Building Information Modelling (BIM) for more accurate construction cost calculations [44, 52, 68].

In eight case studies, LCC was integrated into a broader decision-making framework. The most utilised framework in these cases was the multiple-criteria decision-making (MCDM) technique, employed to determine the optimal solution by amalgamating outcomes from various tools to achieve an integrated value for circularity (or sustainability). The tool combinations within these frameworks varied and included LCA and life cycle impact assessment (LCIA) [22, 35, 45, 72], supplemented by the estimation of annual power consumption and CO₂ emissions [41], and primary embodied energy [46]. Other adopted frameworks include circular life cycle sustainability assessment (C-LCSA), which integrated outcomes from LCA, LCC, social hotspot assessment [43], and eco-efficiency assessment, combining results of LCA and LCC [37]. Examples of outcomes from these frameworks include global sustainability indexes [45] and synthetic economic-environmental indicators [69].

3.4 Methodological gaps and uncertainties

As shown by the number of case studies identified in this study, to date, there remains a limited number of case studies on this topic in published literature, and the largest share of these studies are focused on the direct financial costs. The importance of evaluating environmental impacts is increasingly recognised in CE strategies, as they contribute to reducing the demand for raw materials by prolonging product life cycles and closing material loops. Estevan et al. [82] argue that without monetising environmental and social impacts, LCC alone cannot indicate circular practices, as it fails to address all three dimensions of sustainable development concurrently. Integrating environmental and social impacts into LCC is one solution to address this issue. Another solution observed in case studies is integrating LCC outcomes with those of other tools, such as LCA and MCI, to develop a comprehensive sustainability or circularity metric. MCDM and C-LCSA are identified as frameworks that can facilitate this integration. While some LCC applications do consider environmental and social aspects, the focus is often limited to carbon emissions, suggesting a potential need for more understanding regarding the broader impact-effect relationships or their economic valuation. The uncertainty surrounding the monetary valuation of externalities hinders the inclusion of external effects within the system boundaries of LCC [82], leading to significant variations in the social cost of carbon across studies [64].

Furthermore, various case studies highlighted uncertainties surrounding financial cost data for applications of CE strategies. The innovative nature of these strategies often leads to a lack of data and information during the initial building life cycle stages, particularly concerning product and material prices and construction stage costs [83]. This data gap is identified in several case studies [37, 56]. The long assessment period of the LCC, necessary to encompass cradle-to-grave stages, poses challenges related to future costs, especially during the end-of-life stage. This complicates estimating costs related to dismantling, transportation to waste management sites, and waste disposal or recovery [48]. This challenge arises from uncertainties in the evolution of external factors, such as resource scarcity and waste disposal regulations, which could influence the future value

of materials [20]. Furthermore, authors have highlighted the lack of research on estimating residual value [13], making it challenging to quantify this benefit [80].

The standards and guidance for LCC offer flexibility that allows for adapting the model to suit the specific needs of a product or building. This adaptability facilitates the inclusion of various stakeholder perspectives, for instance, through eLCC or sLCC. However, LCC poses limitations in CE applications due to its linear nature, which is confined by the boundaries of individual building life cycles [19]. There is a notable absence of established standards and knowledge regarding methods to extend LCC to encompass subsequent cycles beyond the initial building life cycle. Conventional LCC faces constraints in accommodating multiple use cycles and allocating costs and benefits across cycles. These limitations primarily stem from treating products as singular components rather than composites of various components and parts.

3.5 Illustrative case studies

To demonstrate the diversity and novelty of LCC applications within circular building construction, four illustrative case studies were selected from the reviewed literature. These examples were chosen to represent cases that extend the conventional LCC framework in distinct and innovative ways. The selection criteria focused on studies that (1) introduced methodological adaptations aligning LCC with Circular Economy (CE) principles, (2) incorporated multiple life cycles or value chain perspectives, (3) integrated LCC with other analytical tools such as LCA or MCDM, and (4) provided clear insights into stakeholder interactions or decision-making processes. Together, these cases exemplify emerging directions in adapting LCC for circularity assessment and highlight methodological innovations that address key limitations identified in the broader literature.

The research conducted by Wouterszoon Jansen et al. [20] introduced a novel LCC model named circular economy life cycle costing (CE-LCC) to evaluate the economic performance of a circular kitchen compared with a conventional kitchen with three circular variants. These featured click-on connections instead of adhesive bonding, enhancing flexibility during the use stage, extending the kitchen's overall lifespan, and enabling remanufacturing and recycling at the end of its life cycle. The CE-LCC tool was developed to aid decision-making in product development by computing the total cost from cradle to grave. The developed CE-LCC assessed the circularity aspect of the circular kitchens using three key approaches. First, the CE-LCC accounted for multiple use cycles at the component and part levels within a use cycle of the product. This allowed components' and parts' functional and technical lifespans to differ in the CE-LCC model. Second, the model accounted for value retention processes (representing the R-imperatives of a CE), distinguishing the circularity of the model from linear ones by allowing a new use cycle to take place beyond the end of use. Third, the model was structured into three stakeholder domains according to where costs occur: the domains of the manufacturer, customer and end-of-use actors. This illustrated the interdependent relationships between stakeholders, understanding the impact of decisions in one domain on the rest. In turn, the outcome of the CE-LCC was the sum of the costs of the three stakeholder domains for the whole product throughout the assessed time, thus providing a more comprehensive perspective on the economic performance of circular product designs.

In their case study, Kulakovskaya et al. [74] focused on the EPS value chain and examined the potential environmental and economic benefits of recycling EPS. The study employed a comprehensive approach combining MFA, LCA, LCC, and scenario development. LCC was adopted to measure the economic impacts of five recycling scenarios for EPS waste and the business as usual. The tool was applied to the entire Swiss building stock and conducted from the perspective of the entire value chain, due to the wider impacts of transitioning from a linear to a CE. Through the application of this perspective, the study assessed how and to what extent individual value chain players are affected by the CE model of EPS recycling.

The research conducted by Tanthanawiwat et al. [76] is noteworthy for its comprehensive approach to integrating and monetising the full environmental impact in LCC. The case study compared CE scenarios for managing construction and demolition waste with a landfilling base case, focusing on waste from concrete and timber houses. The methodology adopted was MCI, LCA, and LCC separately. In addition to recovery operations' financial and operational costs, the LCC included the externalised costs of 10 impact categories identified in the LCA. These categories encompass global warming, fine particulate matter formation, ozone formation, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, mineral resources scarcity, land use, and fossil resource scarcity.

The case study conducted by Tighnavard Balasbaneh et al. [46] investigated the circularity of various formwork materials used in concrete construction to assess their reusability potential across multiple use cycles. To determine the optimal formwork material, the researchers applied MCDM analysis using Analytic Hierarchy Process (AHP) technique. Weightings were assigned to the following seven criteria based on their relative importance based on expert opinion: global warming potential, terrestrial acidification potential, human non-carcinogenic toxicity, ozone formation, human health, fossil resource scarcity, embodied energy, and life cycle costs. Through the AHP technique, the results of the LCA and LCC were normalised and weighted, and differences between alternative solutions were calculated using specified equations to estimate performance scores.

4 Conclusions

This study systemically reviewed 51 peer-reviewed case studies to investigate current practices of applying LCC to the CE of building construction, aiming to address the existing gap in the literature on the subject. Following a structured framework, this paper identified seven key types of CE strategies in LCC literature for the building construction sector. This comprised of (1) material/product reuse, (2) secondary material, (3) recycling processes, (4) recovery potential at end of life, (5) demountable and/or adaptable solutions, (6) maintenance and repairs, and (7) refurbishment and regeneration, with the latter two serving as strategies for delaying deconstruction. These strategies are implemented across all building life cycle stages, from material manufacturing and construction to maintenance and renovation and end of life, demonstrating that circularity is increasingly embedded in decision-making beyond the design phase.

Across the reviewed studies, LCC serves primarily as a decision-support tool within CE strategies in the building construction sector to compare circular and conventional solutions. It enables the determination of optimal maintenance, repairs, and renovation

strategies, supports decisions on construction and demolition waste management during end of life, and assesses the adequacy of incentives for circular practices, including the identification of potential conflict of interest between stakeholders. The review found that *flLCC* remains dominant, while *eLCC*, *feLCC*, and *sLCC* are emerging as important extensions that incorporate environmental and social externalities. These variations expand the analytical scope of LCC beyond purely economic considerations, reflecting a gradual shift towards more comprehensive sustainability assessments.

Furthermore, the LCC scope has been extended beyond the conventional building owner perspective to encompass broader stakeholder viewpoints. Most studies apply a cradle-to-grave boundary, but an increasing number adopt non-linear or extended boundaries, such as grave-to-cradle, to capture material recovery and multiple use cycles. Approximately 60% of the reviewed studies include residual value or avoided resource use beyond the building life cycle, signalling progress towards more circular interpretations of cost boundaries and stakeholder perspectives.

Nonetheless, several methodological challenges remain, including the absence of standardised frameworks for adapting linear LCC models to multiple use cycles, limited data availability for innovative CE strategies, and persistent uncertainties in estimating residual value, future cost data, and external cost monetisation.

Overall, the results indicate that LCC is increasingly recognised as an essential instrument for evaluating and promoting circularity in the building construction sector, by integrating economic, environmental, and social dimensions within a life cycle perspective. However, its application to CE remains in an early stage, with further refinement needed to enhance its consistency, comparability, and practical relevance.

The findings of this review provide important implications for scholars, practitioners, and policymakers. For researchers, the study offers a structured synthesis of methodological variations in applying LCC to circular building construction, identifying gaps that can guide future model development and standardisation efforts. For practitioners, the insights on how LCC has been combined with other tools and applied across different life cycle stages can inform more integrated and cost-effective decision-making in circular projects. For policymakers, the results underline the need to support the wider adoption of LCC through harmonised guidelines, data-sharing frameworks, and incentives that recognise the long-term economic value of circular strategies in the building sector.

4.1 Limitations and future research directions

While this review provides a comprehensive review of LCC applications in the circular economy of building construction, several limitations should be acknowledged. Although the paper systematically examines methodological aspects of LCC, it does not evaluate the consistency or quality of implementation across the reviewed case studies, which may affect comparability of results. Moreover, the focus on building- and component-level case studies limits the generalisability of findings to broader system scales such as infrastructure. Finally, this review does not compare the economic effectiveness of circular strategies with linear approaches. Future research could build on this work by systematically reviewing the economic viability of circular economy strategies to deepen the evidence on financial drivers of circular transitions.

Furthermore, this review has identified several critical gaps in current research and practice that warrant further investigation. These gaps can be categorised into three main areas: methodological standardisation, data requirements, and implementation challenges.

First, there is a pressing need for standardisation of LCC methodology in the CE context. While current LCC standards provide a foundation for cost assessment, they are primarily designed for linear life cycle thinking. Future research should focus on developing standardised approaches for incorporating multiple life cycles, essential for adequately evaluating CE strategies. Additionally, methods for consistently valuing residual value must be established, as current approaches vary significantly across studies. While this need is relevant for any application context, irrespective of whether the analysed system is linear or circular, the residual value in a CE LCC is central to assessing the circularity of the assessed products or practices. Integrating environmental and social costs into LCC frameworks also requires standardisation to ensure comparable and reliable assessments of CE principles in building construction.

Second, the availability and quality of data emerge as significant constraints. Current literature reveals limited data availability for innovative CE strategies, particularly regarding their long-term performance and end-of-life scenarios. Future work should prioritise the development of comprehensive databases for end-of-life costs and standardising cost data collection and reporting methods. This standardisation would enable more accurate comparisons between conventional and CE strategies while reducing uncertainty in long-term cost projections.

Third, implementation challenges must be addressed to facilitate wider adoption practices of LCC in CE. Research should investigate the barriers that prevent practitioners from adopting LCC in CE and develop strategies to overcome these obstacles. Furthermore, research should explore how LCC can effectively integrate existing building assessment methods to create more comprehensive evaluation frameworks for the CE.

These research directions are crucial for advancing the field and supporting the transition toward circular practices in the building construction sector. Addressing these gaps would significantly improve the reliability and practical applicability of LCC in CE as a decision-making tool for circular buildings.

Abbreviations

AHP	Analytic Hierarchy Process
BCI	Building Circularity Indicator
BIM	Building Information Modelling
CE	Circular Economy
CE-LCC	Circular Economy Life Cycle Costing
C-LCSA	Circular Life Cycle Sustainability Assessment
CO ₂	Carbon Dioxide
eLCC	Environmental Life Cycle Costing
EPS	Expanded Polystyrene
feLCC	Full Environmental Life Cycle Costing
fLCC	Financial Life Cycle Costing
GDP	Gross Domestic Product
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
MCDM	Multiple-Criteria Decision-Making
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
sLCA	Social Life Cycle Assessment
sLCC	Social Life Cycle Costing
TCO	Total Cost of Ownership

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Author contributions

A.V. wrote the main manuscript text and developed the framework for identifying and assessing the relevant literature. A.V. and H.A.G. selected the relevant papers and assessed them using the developed framework. A.V., H.A.G., W.C.L., and M.R. reviewed the manuscript.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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