ISSN: 1648-6897 / eISSN: 1822-4199

VILNIUS TECH
Vilnius Gediminas Technical University

JOURNAL of ENVIRONMENTAL ENGINEERING & LANDSCAPE MANAGEMENT

2026
Volume 34
Issue 2
Pages 186–197
https://doi.org/10.3846/jeelm.2026.27214

INSIGHTS INTO THE ENTIRE BUILDING LIFE CYCLE ASSESSMENT (LCA): EXISTING TRENDS, CHALLENGES AND PROSPECTIVE FRAMEWORK

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Highlights:

- whole-life LCA integration is critical for credible sustainability index development;
- early design decisions determine long-term environmental performance outcomes;
- expansion of EPD data and regulation strengthens life-cycle-based assessment.

Article History:

- received 22 April 2026
- accepted 27 May 2026

Abstract. Building sustainability assessment increasingly demands life cycle coverage that captures environmental burdens and trade-offs beyond operational energy, including embodied impacts and end of life (EoL) outcomes under circular economy (CE) pathways. This review synthesises recent research on how Life Cycle Assessment (LCA) supports the formation of Building Sustainability Index (BSI), with particular attention to the stage-dependent distribution of impacts and the growing significance of embodied and EoL stages in low-energy buildings, methodological sensitivities associated with system boundaries, datasets, and scenario definitions, and the implications of EoL modelling and allocation choices for CE-oriented sustainability claims. The paper further examines how life cycle thinking is operationalised within major certification schemes (LEED, BREEAM and DGNB) and discusses comparability limitations when certification outcomes are interpreted as sustainability indices. By consolidating methodological evidence and practice-oriented pathways, the paper clarifies requirements for robust, transparent and comparable Life Cycle Assessment (LCA) informed sustainability indices aligned with whole-life and circularity objectives.

Keywords: Life Cycle Assessment (LCA), Building Sustainability Index (BSI), sustainability certification systems, Artificial Intelligence (AI), circular economy, environmental burdens.

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1. Introduction

The integration of sustainability into the built environment has become a critical priority due to the construction sector's substantial contribution to global environmental impacts. At a global scale, the buildings and construction sector accounts for approximately 36–39% of final energy consumption and around 37% of energy and process-related CO_2 emissions worldwide (International Energy Agency, 2019). In addition to operational energy use, buildings generate significant embodied impacts through material production, construction activities, maintenance, and end of life (EoL) processes, highlighting the limitations of assessments focused solely on the use phase.

Building sustainability is therefore increasingly understood as a multi-dimensional concept encompassing environmental, economic, and social considerations across the entire building life cycle. Within this context, Life Cycle Assessment (LCA) has emerged as a core methodological framework because it enables systematic, cradle-to-grave quantification of environmental impacts associated with material extraction, construction, operation, and EoL stages (Kofoworola & Gheewala, 2008; Lasvaux et al., 2015; Dsilva et al., 2023, Liu et al., 2023). By providing impact-based evidence across life cycle stages, LCA supports transparent comparison of design alternatives and reduces the risk of burden shifting between phases (Braganca et al., 2010; Xue et al., 2021).

The role of LCA within building sustainability assessment can be further clarified through a hierarchical perspective of life cycle-based evaluation approaches. As illustrated in Figure 1, sustainability assessment methods can be conceptualised as progressing from a basic life cycle perspective toward more integrated frameworks that combine multiple impact categories and sustainability dimensions. Within this hierarchy, LCA forms the analytical core that enables a transition from single issue indicators, such as carbon or water footprints, to more comprehensive environmental assessment, and ultimately to integrated Life Cycle Sustainability Assessment (LCSA) approaches that incorporate environmental, economic, and social dimensions (Finkbeiner et al., 2010; Schneider-Marin et al., 2022).

Against this background, this review examines the assessment of the Building Sustainability Index over the entire building life cycle using Life Cycle Assessment as a unifying methodological foundation. The paper synthesises evidence on the distribution of environmental impacts across life cycle stages, analyses how LCA is embedded within major building sustainability certification systems and the implications for interpreting certification outcomes as sustainability indices and discusses the emerging role of digitalisation and artificial intelligence in enabling scalable, transparent, and updateable LCA based BSI. This review also provides a conceptual framing of life cycle-based sustainability indicators, positioning LCA as the analytical core of Building Sustainability Index development.

2. Methods

This review adopts a structured narrative literature review approach to synthesise research on Building Sustainability Index (BSI) and indicator-based sustainability assessment frameworks across the entire building life cycle, with particular emphasis on the role of Life Cycle Assessment (LCA). The framework of the methodology for the review are presented in Figure 2.

The identified sources were screened using predefined inclusion and exclusion criteria. Studies were included if they contributed to the methodological development of sustainability indicators or indices, explicitly addressed whole-life or life cycle-oriented building assessment, or were relevant to the practical implementation of sustainability assessment frameworks. Attention was given to studies addressing LCA-based indicator formation, life cycle stage-related environmental impacts, certification system integration, and the role of digital tools in sustainability assessment. Studies limited to single descriptive case analyses without broader methodological relevance were excluded from the primary analytical dataset.

The selected literature was subsequently analysed using a thematic synthesis approach. The analysis focused on four main thematic strands. First, the review examined the role of LCA as the methodological foundation of BSI formation. Second, it synthesised evidence on the relative influence of different life cycle stages on building sustainability outcomes. Third, it analysed how LCA is integrated into major building sustainability certification systems and how certification results are interpreted as sustainability indices. Fourth, it reviewed the emerging contribution of digitalisation and artificial intelligence to LCA-based sustainability assessment and index development.

The results of this thematic synthesis were used to develop a conceptual framework describing how life cycle-based environmental evidence, certification logic, and digital support tools contribute to the formation of a Building Sustainability Index.

The methodological workflow presented in Figure 2 summarises the main stages of the literature review process, including literature identification, screening based on predefined inclusion criteria, thematic analysis, and synthesis of findings relevant to the development of LCA-based Building Sustainability Index. This structured approach ensures a systematic and transparent evaluation of the selected literature and supports the identification of key methodological themes addressed in this review.

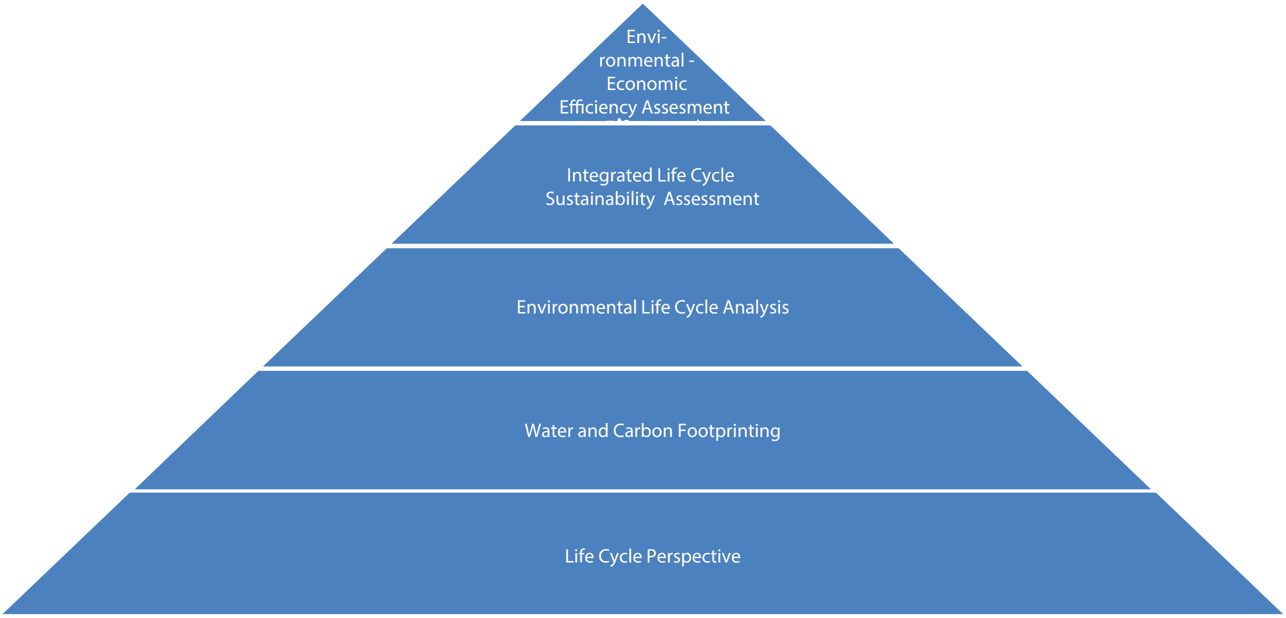

Figure 1. Life cycle concept in hierarchy structure

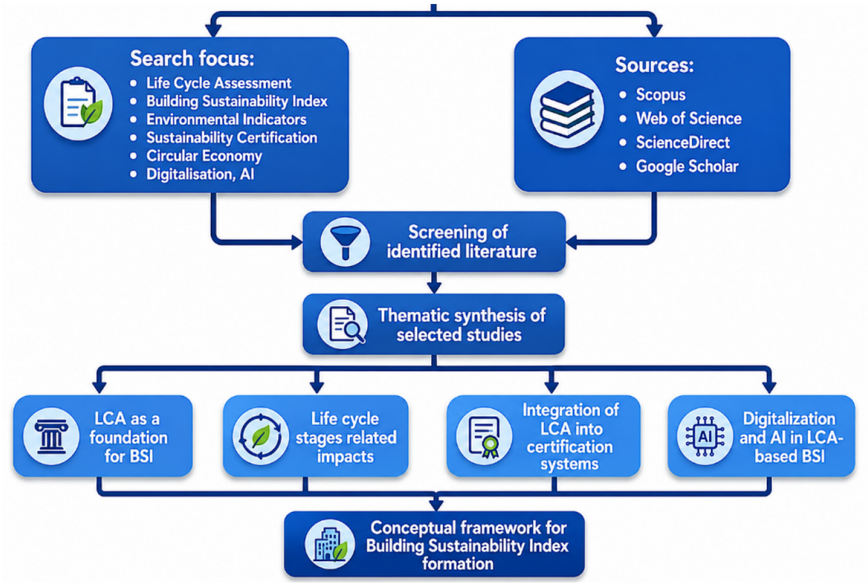

Figure 2. The framework of the methodology for the review

3. Analysis of the main aspect for the model creation to building sustainability index assessment

3.1. Design and construction stage in LCA-based Building Sustainability Index development

The relevance of Life Cycle Assessment to sustainability index formation is strongly linked to its ability to capture the differentiated impacts associated with distinct building life cycle stages (Hollberg & Ruth, 2016). Standard LCA frameworks typically consider phases ranging from raw material extraction and product manufacturing to construction, operation, maintenance, and end of life processes, including demolition, reuse, and recycling (Braganca et al., 2010; Ylmén et al., 2019). Each of these stages contributes differently to the overall sustainability performance of a building and therefore requires appropriate representation within sustainability indices. The literature review analysis on LCA-based Building Sustainability Index development is presented in Table 1.

In the context of sustainability index development, the definition of system boundaries represents a critical methodological decision, as it determines which life cycle stages and impact sources are included in the assessment (Egemose et al., 2022). In this review, the life cycle structure is conceptualised in accordance with the principles and modular structure defined in EN 15978 (European Committee for Standardization, 2022), adopting a cradle-to-grave perspective that encompasses material production, construction, operational and maintenance activities, and end of life processes. In addition, potential benefits occurring beyond the assessed building life cycle such as reuse, recycling, and recovery pathways are acknowledged through an extended system perspective consistent with the EN 15978 framework. The adopted system boundary and life cycle stage structure are schematically illustrated in Figure 3.

Research indicates that early life cycle stages, particularly material production and construction, are closely associated with embodied environmental impacts, which can account for a substantial share of total life cycle emissions, especially in energy-efficient and low-operational-energy buildings (Lasvaux et al., 2015; Lee et al., 2015). Conversely, the operational phase remains a dominant contributor to energy consumption and emissions over long service lives, highlighting the need for sustainability indices to balance short-term embodied impacts with long-term operational performance (Ylmén et al., 2019; Xue et al., 2021).

End of life stages are increasingly recognised as critical components of life cycle–oriented sustainability assessment, particularly in the context of circular economy strategies (Wong & Fan, 2013). LCA-based studies demonstrate that assumptions related to demolition practices, material recovery, and recycling rates can significantly influence overall sustainability outcomes (Xue et al., 2021; Dsilva et al., 2023). Consequently, sustainability indices that exclude or oversimplify end of life considerations risk underestimating both environmental burdens and potential benefits associated with circular material flows.

The differentiated contribution of life cycle stages underscores the importance of stage specific weighting and transparent system boundaries in sustainability index formation. Several authors note that partial life cycle coverage, as often observed in certification-based assessments, may distort sustainability rankings and limit comparability across projects (Onat et al., 2017; Larsen et al., 2022). Therefore, LCA based sustainability indices benefit from explicitly linking impact categories and performance indicators to specific life cycle stages, ensuring that sustainability assessments reflect the full temporal and functional scope of building performance.

Table 1. The literature review analysis on LCA-based Building Sustainability Index development

			References																	
No.	Factors / Themes	Group	Kofoworola and Gheewala (2008)	Braganca et al. (2010)	Finkbeiner et al. (2010)	Lasvaux et al. (2015)	Lee et al. (2015)	Hollberg and Ruth (2016)	Bernardi et al. (2017)	Onat et al. (2017)	Pomponi and Moncaster (2016)	Cordero et al. (2019)	Rosario et al. (2021)	Larsen et al. (2022)	Mirzaie et al. (2020)	Gulck et al. (2022)	Dsilva et al. (2023)	Hong et al. (2020)	Chen et al. (2023)	Yavan et al. (2024)
1	LCA as a methodological framework for sustainability assessment	LCA methodology	✓	✓	✓	✓				✓				✓			✓			
2	System boundary definition in building LCA studies		✓	✓		✓		✓		✓			✓	✓		✓	✓			
3	Whole-life life-cycle perspective in sustainability assessment	Life-cycle assessment scope	✓	✓		✓		✓		✓	✓			✓						
4	Embodied environmental impacts from materials and construction					✓	✓				✓						✓			
5	Operational stage environmental performance										✓			✓						
6	Integration of LCA within building certification systems	Certification frameworks		✓					✓			✓		✓						
7	Use of Environmental Product Declarations (EPDs) and databases	Data sources and inventories				✓							✓	✓			✓			
8	BIM integration supporting life-cycle environmental assessment	Digitalisation and modelling tools					✓	✓											✓	✓
9	Circular economy and end-of-life modelling in building LCA	Circular economy aspects									✓			✓	✓	✓				
10	Artificial intelligence for sustainability assessment and LCA support	Artificial intelligence applications																✓	✓	✓

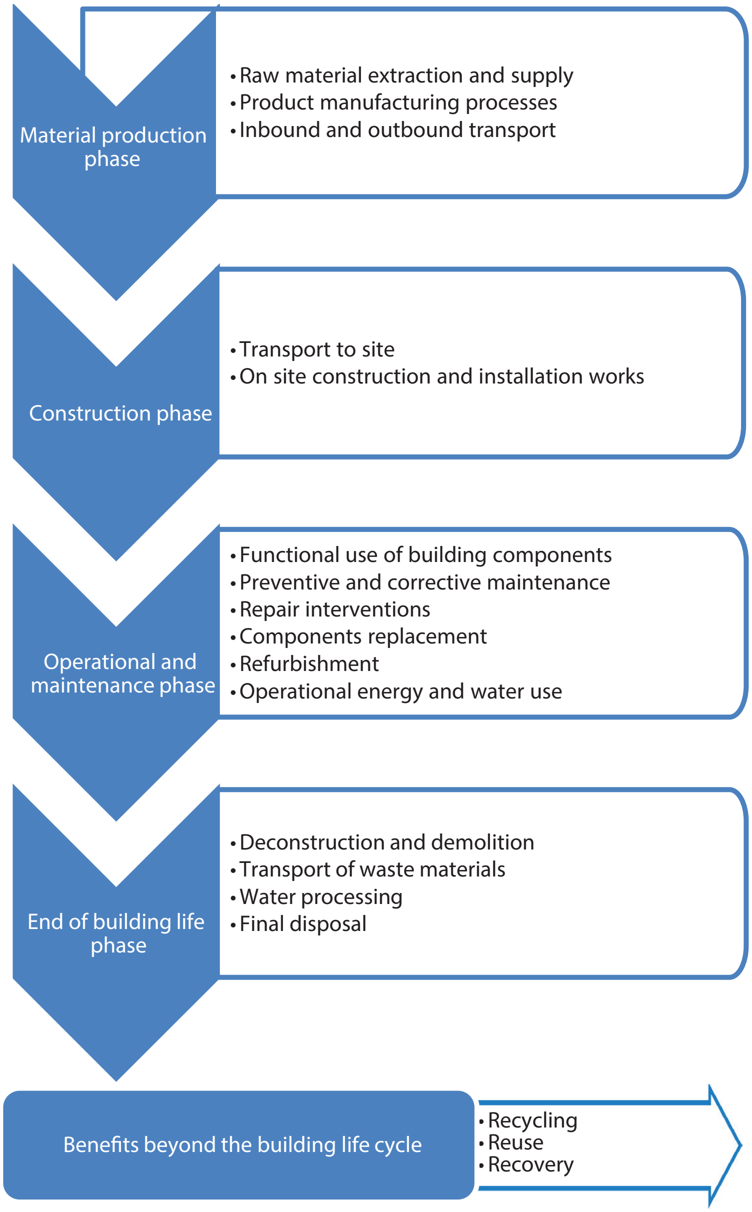

Figure 3. Assessment system boundary and life cycle phases applied in the evaluation of the Building Sustainability Index, based on EN 15978

The life cycle structure illustrated in Figure 3 provides the methodological foundation for constructing a Building Sustainability Index grounded in Life Cycle Assessment.

Life Cycle Assessment (LCA) is widely applied to understand how environmental impacts are distributed across the building life cycle and how trade-offs between stages shape overall sustainability outcomes. Evidence from the literature indicates that the relative contribution of life cycle stages is not fixed: it depends on building type, service life, energy system boundary conditions, climate, and methodological choices (Khasreen et al., 2009; Finnveden et al., 2009; Häfliger et al., 2017). This section synthesises current knowledge on the relative influence of design and construction decisions, operational performance, and end of life strategies, and highlights why stage interactions are critical for robust building sustainability assessment.

Decisions taken at the design and construction stages have long-lasting effects because they determine key parameters that remain “locked in” over the building’s service life, including material composition, structural solutions, envelope performance, and adaptability potential (Khasreen et al., 2009; Zabalza et al., 2013). From an LCA perspective, these decisions strongly influence embodied impacts particularly those associated with raw material extraction, processing, and product manufacturing (Cabeza et al., 2021; Gomes et al., 2019).

Material selection is frequently identified as a dominant driver of embodied environmental impacts.

Literature mapping studies indicate that embodied energy and embodied carbon are highly material-dependent and that progress in mitigation is constrained by data limitations and decision-making barriers within design practice

(Cabeza et al., 2021). In parallel, LCA sensitivity research demonstrates that modelling choices for construction materials can substantially alter environmental results, which has implications for comparability and for how sustainability indices interpret better solutions (Häfliger et al., 2017). These findings support the argument that sustainability indices should explicitly account for the uncertainty and variability associated with material-related assumptions.

The growing use of Environmental Product Declarations (EPDs) has substantially improved the availability of material-specific life cycle data for early design decision-making. This trend is reflected in the steady increase in the number of registered EPDs worldwide, with particularly strong growth observed since 2020. Despite this expansion, construction products still account for a relatively limited share approximately one eighth of all registered EPDs, highlighting both progress and remaining gaps in data coverage across the building materials sector. Because EPDs are typically developed in accordance with EN 15804, they provide a standardized and LCA-compatible basis for quantifying embodied environmental impacts at the design stage. However, the uneven distribution of EPDs across product groups means that early-stage assessments often rely on a mix of product-specific and generic data, reinforcing the importance of transparency and uncertainty awareness when sustainability indices aggregate material-related impacts.

Taken together, the evidence presented in Figure 3 indicates that the expanding availability of EPD-based life cycle data is creating new opportunities to inform material-related decisions at early design stages. At the same time, the uneven coverage of construction products and the variability of available datasets suggest that such information can only deliver its full value when it is systematically embedded within structured assessment processes. This reinforces the importance of integrating life cycle-based evaluation methods into the design workflow rather than treating environmental data as an isolated input.

Integrating LCA earlier in the design workflow is repeatedly emphasized to improve decision quality. BIM-based approaches can support rapid comparison of alternatives and enable more dynamic sustainability evaluation, including alignment with certification-related requirements (Azhar et al., 2011; Meex et al., 2018; Carvalho et al., 2021). Review evidence suggests that BIM capabilities can increase the feasibility of applying life cycle energy and environmental evaluation in practice, especially when the aim is to identify design-stage levers with the highest long-term influence (Eleftheriadis et al., 2017; Soust-Verdaguer et al., 2017; Li et al., 2023). Overall, the literature converges on the conclusion that design and construction decisions are pivotal not only because they shape embodied impacts, but also because they constrain future operational performance and end of life recoverability.

3.2. Operational phase and building performance efficiency

The operational phase is widely recognised as one of the most influential stages in whole life environmental performance due to the cumulative effect of energy consumption and associated emissions over long building service lives (Finnveden et al., 2009; Gardner et al., 2020). In many contexts, operational energy use can outweigh the environmental impacts associated with initial construction, particularly in buildings with conventional energy performance levels or extended operational lifetimes (Gardner et al., 2020; Chandrasekaran & Dvarionienė, 2022).

Digital tools are increasingly applied to support the assessment and management of operational performance, particularly in the context of building upgrades and long-term performance improvement strategies. Building Information Modeling (BIM) enabled approaches facilitate the integration of environmental and economic evaluation across life cycle stages and support the systematic comparison of operational improvement measures using consistent datasets (Carvalho et al., 2020, 2021). In addition, the integration of BIM with Internet of Things (IoT) technologies enables enhanced data flow and real time monitoring of energy use and system performance during operation, providing a feedback mechanism to verify, adjust, and optimise renovation and maintenance interventions over time (Chen et al., 2023). From a sustainability assessment perspective, these developments support a transition toward adaptive operational evaluation, in which operational performance is continuously informed by measured data and aligned with long-term life cycle objectives.

In addition to digital assessment frameworks, sustainable building modernisation constitutes an important pathway for achieving long-term operational performance objectives.

The literature reviewed indicates a progressive reduction in annual primary energy consumption and associated CO_2 emissions over time, with projected reductions of more than 50% in primary energy use and near-zero operational emissions by 2050 relative to the 2020 baseline. Although the specific reduction targets vary depending on the analysed context, the reviewed studies consistently demonstrate that life cycle-informed modernization strategies can deliver substantial long-term operational benefits. These findings further support the inclusion of operational performance trajectories within sustainability indices intended to capture whole-life building performance.

The projected trends highlight the scale of operational performance improvements that can be achieved through coordinated modernization strategies applied at the building stock level. The progressive reductions in primary energy consumption and operational CO_2 emissions illustrate how long-term, life cycle-informed interventions can shift the operational phase from being the dominant source of environmental burdens towards a substantially mitigated contributor. From a sustainability index perspective, such trajectories emphasize the importance of representing not only current operational performance but also anticipated long-term performance pathways when assessing whole life building sustainability.

3.3. End of life stage and circular economy aspects

The end of life (EoL) stage plays a decisive role in building sustainability assessment due to the increasing integration of circular economy (CE) principles into policy frameworks, certification schemes, and life cycle-based decision making (Walker et al., 2018).

Evidence from LCA literature shows that EoL modelling assumptions including demolition versus deconstruction practices, recycling and recovery rates, substitution effects, and reuse potential can significantly influence life cycle results and sustainability rankings (Mirzaie et al., 2020; Lei et al., 2023). These effects are particularly pronounced for structural and envelope systems, where material choice, connection detailing, and documentation determine the feasibility of disassembly and high-quality material recovery (Kakkos & Hischier, 2022; Trubina et al., 2024). As a result, EoL performance is strongly path-dependent and cannot be decoupled from earlier design and construction decisions.

Despite this relevance, EoL is frequently underrepresented in applied sustainability assessments. Many assessments rely on simplified or generic scenarios, even though case-based studies demonstrate that alternative EoL strategies such as reuse, remanufacturing, and recycling can lead to substantially different environmental outcomes depending on scenario definitions and methodological choices (Wolf et al., 2020; Lei et al., 2023). Circular economy-oriented research further highlights that robust assessment requires consistent modelling of material flows across life cycle stages and transparent allocation of burdens and benefits associated with recycling and reuse, including effects occurring beyond the assessed system boundary (Eberhardt et al., 2020; Gulck et al., 2022). Inconsistent treatment of these aspects risks biasing sustainability scores in favour of or against circular strategies due to accounting conventions rather than actual performance.

From a BSI perspective, these findings imply that the EoL stage should be conceptualised as a scenario space rather than a fixed endpoint. Sustainability indices intended to support circular decision-making must therefore capture alternative EoL pathways and reflect their interactions with upstream design choices.

3.4. Integration of LCA into building sustainability certification systems

Life Cycle Assessment (LCA) is increasingly incorporated into building sustainability certification systems as a means of moving beyond fragmented, theme-based indicators toward a more comprehensive life-cycle-oriented evaluation of environmental performance.

Strategies related to adaptability, disassembly, and reuse can influence environmental impacts differently across life cycle stages, and LCA provides a necessary analytical basis for evaluating whether such strategies result in net environmental benefits rather than impact shifting (Blomsma & Brennan, 2017; Pomponi & Moncaster, 2017). In this respect, LCA strengthens the environmental credibility of circularity-oriented credits and labels by grounding them in quantified whole-life performance.

The growing role of LCA within building sustainability certification systems reflects a broader transition toward quantified, life-cycle-based performance assessment. At the same time, differences in how LCA is embedded across certification schemes particularly with respect to system boundaries, data sources, and life cycle stage coverage have important implications for the interpretation and comparability of certification outcomes when they are used as indicators of building sustainability.

4. Scope and principles of LCA integration in building sustainability certification systems

The integration of Life Cycle Assessment (LCA) into building sustainability certification systems represents a methodological shift from fragmented, theme-based indicators toward a coherent, whole life-cycle-based evaluation of building environmental performance.

In practice, LCA integration typically operates at two interconnected levels: product-level environmental information and whole-building environmental performance modelling (Lasvaux et al., 2015; Rosario et al., 2021). However, the coexistence of generic datasets and multiple product- or company-specific EPDs for similar materials introduces methodological challenges, making it necessary for certification systems to clearly define how product-level data are incorporated into whole-building LCA calculations to ensure consistency and comparability (Lasvaux et al., 2015).

The scope of LCA integration is also inseparable from life-cycle stage coverage. Although LCA is fundamentally defined as a method spanning stages from raw material extraction to end-of-life, certification practice has historically prioritised the operational phase, particularly energy use. Earlier stages raw material extraction, product manufacturing, and construction as well as end-of-life processes have often been addressed only partially or indirectly. This imbalance is increasingly problematic, as the relative contribution of different life-cycle stages varies significantly depending on building type, energy-efficiency level, and material composition, meaning that an operationally focused assessment does not necessarily reflect total life-cycle environmental performance (Bernardi et al., 2017; Larsen et al., 2022; Binz & Jäger, 2024).

In response, the scope of LCA integration within certification systems has gradually expanded beyond new construction to include refurbishment, retrofit, and adaptive

Figure 4. Intervention pathways considered within the scope of LCA-based building sustainability assessment

reuse interventions. LCA is widely applied to compare alternative intervention strategies and to assess the environmental implications of refurbishment decisions, thereby providing a robust methodological basis for certification schemes that seek to evaluate the sustainability of the existing building stock (Kim et al., 2021; Strzelecki et al., 2025). This broader scope supports whole-life decision-making and allows certification systems to better reflect sustainability priorities within the built environment.

Finally, end-of-life and construction and demolition waste scenarios constitute a critical component of LCA scope in certification systems. The literature emphasises that without systematic modelling of end-of-life pathways including recycling, reuse, disassembly, and disposal it is not possible to reliably assess circular strategies or decarbonisation potential, particularly for material-intensive solutions (Dams et al., 2021; Mesa et al., 2021). As a result, the inclusion of end-of-life scenarios is increasingly treated not as an optional extension, but as a necessary element of certification systems that claim whole-life or circular performance.

As illustrated in Figure 4, the scope of LCA integration in building sustainability certification systems extends beyond the mere inclusion of LCA calculations and involves explicit decisions regarding the object of assessment, life-cycle stage coverage, data integration, and the treatment of different intervention types, including new construction, refurbishment, and reuse.

These scoping decisions form the methodological foundation upon which certification results are produced and interpreted, directly influencing their robustness and suitability as indicators of building-level sustainability performance.

4.1. Certification systems as sustainability indices: structural differences in LCA integration

As certification systems increasingly inform investment decisions, public procurement, and policy frameworks, they are frequently treated in practice as de facto sustainability indices. Within this framing, LCA plays a critical role by shifting certification logic from predominantly descriptive requirements toward quantified, impact-based evaluation across multiple environmental categories. Rather than serving as a supplementary calculation tool, LCA increasingly functions as a quantitative backbone underpinning composite sustainability scores.

Nevertheless, certification systems differ fundamentally in how LCA evidence is embedded within their assessment architectures. Credit-based systems prioritise flexibility and accessibility by allowing multiple compliance pathways, whereas performance-based systems integrate mandatory life cycle evaluation more deeply into certification logic.

To clarify how these methodological and structural differences manifest in practice, and how they affect the suitability of certification outcomes as sustainability indices Table 2 compares Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and German Sustainability Building Council (DGNB) with respect to their assessment logic, life cycle stage coverage, data requirements, and implications for sustainability index formation).

Table 2 shows that LEED's flexible, credit driven architecture allows the same certification level to be achieved through different strategies that may yield substantially different life cycle environmental outcomes. As a result, LEED certification functions primarily as a relative performance label rather than a direct proxy for whole-life environmental impact. BREEAM occupies an intermediate position, retaining a credit-based structure while increasingly embedding LCA and circular economy indicators within a European standards-oriented framework. DGNB, by contrast, is explicitly designed as a life cycle performance-based sustainability system, in which LCA constitutes a mandatory and central quantitative component integrated across environmental, economic, and socio-cultural dimensions from the outset.

These structural distinctions are reflected in how certification systems address individual life cycle stages. At the design stage, LEED encourages early sustainability strategies but does not consistently require quantified LCA, whereas BREEAM more actively incentivizes early-stage life cycle thinking, particularly for material-related impacts. DGNB places strong emphasis on early-stage LCA modelling as a prerequisite for informed decision-making, positioning LCA as a design support and optimisation tool rather than a post hoc verification exercise. Similar patterns are observed across construction, operational, and end of life stages, where DGNB systematically requires quantified assessment, while LEED and BREEAM may address these stages indirectly or selectively through credits.

5. Conclusions

The reviewed literature published between 2008 and 2026 demonstrates a clear increase in research attention devoted to life-cycle-based building sustainability assessment, particularly in relation to embodied impacts, circular economy strategies, and digitalised sustainability evaluation approaches. This growing body of work reflects the

Table 2. Comparative table of certification systems for the sustainability index

Criterion	LEED	BREEAM	DGNB
Role of certification system as sustainability index	Credit-based, flexible rating; functions as a relative performance label, not a direct proxy for life cycle environmental magnitude. Scores can mask LCA hotspots due to point aggregation	Credit-based but more structured; increasingly used as a semi-quantitative index, especially in European contexts with stronger LCA alignment	Designed explicitly as a life cycle performance-based sustainability index, integrating environmental, economic, and socio-cultural dimensions from the outset
Explicit LCA requirement	LCA is optional or credit-driven; used mainly for comparative assertions rather than mandatory whole-life evaluation	LCA is integrated more systematically for materials and environmental performance, though still partly credit-driven	LCA is mandatory and central to assessment logic, forming a core quantitative backbone of the system
Alignment with EN 15804 / EN 15978	Limited and indirect; system originally developed outside European standardisation context	Stronger alignment with European standards; EN-based LCA increasingly embedded in assessment logic	Explicitly aligned with EN 15804 and EN 15978, enabling standardised life cycle scenario definition and comparability
Design stage	Encourages early design strategies but allows multiple compliance pathways that may not require quantified LCA	Actively incentivises early stage life cycle thinking, particularly for materials and embodied impacts	Strong emphasis on early-stage LCA modelling as a prerequisite for informed design decisions
Construction stage	Typically underrepresented; impacts may be indirectly addressed via credits rather than quantified LCA	More explicit consideration of construction impacts, though often scenario-based	Quantitatively addressed within LCA scope, supporting more complete life cycle coverage
Operational stage	Historically dominant focus; operational energy strongly weighted relative to embodied impacts	Balanced treatment of operational and embodied impacts, with growing emphasis on whole-life performance	Integrated treatment of operational impacts within life cycle framework, avoiding over-weighting single stages
End of life stage	Frequently simplified or generic; EoL often weakly linked to design decisions	EoL increasingly addressed, particularly where circularity credits are claimed, but scenario definitions vary	Explicit EoL modelling required, including demolition/deconstruction scenarios consistent with standards
Beyond system boundary (circularity)	Limited and inconsistent; circular benefits may be credited qualitatively	Partial treatment of circular benefits; depends on specific credits and assessor interpretation	Systematically included, enabling consistent accounting of reuse, recycling, and recovery benefits
Overall suitability for a life cycle-based BSI	Low moderate, requires strong post-processing and harmonisation to function as an index	Moderate high, increasingly compatible with BSI logic when LCA scope is clearly defined	High, structurally aligned with BSI principles and life cycle sustainability assessment (LCSA)

increasing importance of whole-life environmental performance, embodied impacts, circular economy strategies, and the integration of digital tools into sustainability evaluation. The thematic synthesis conducted in this review further indicates that the literature most consistently emphasises LCA as the methodological backbone of building sustainability assessment, together with whole-life stage coverage, system boundary definition, and the integration of environmental evidence into broader sustainability frameworks.

Across the literature, the relative influence of life cycle stages is context-dependent and shaped by design and construction decisions that lock in embodied impacts and constrain future operational performance and end-of-life outcomes. As operational energy decreases in low-energy buildings, embodied and end-of-life stages gain increasing importance, making stage trade-offs essential for robust index interpretation. End-of-life modelling and circular economy pathways are major sources of variability in sustainability assessment results because outcomes depend strongly on scenario definitions and allocation choices. Therefore, Building Sustainability Index (BSI) should treat end-of-life (EoL) assessment as scenario-dependent and clearly document all methodological assumptions, including benefits occurring beyond the system boundary.

The review further shows that certification schemes such as LEED, BREEAM, and DGNB differ structurally in how LCA is embedded, limiting the direct comparability of certification outcomes when used as sustainability indices. These differences relate not only to life cycle stage coverage, but also to aggregation logic, data sources, and the treatment of circularity and end-of-life aspects. From a BSI perspective, methodological harmonisation remains essential for improving transparency, robustness, and comparability across building sustainability assessments.

Finally, digitalisation and artificial intelligence can improve the scalability and practical applicability of LCA-based BSI through automated inventory generation, early-stage impact prediction, and dynamic updates across the building life cycle. However, these developments do not replace the need for standards-consistent boundaries, transparent data provenance, and explicit communication of uncertainty. Overall, the findings of this review indicate that robust BSI development depends on the combined integration of life cycle thinking, methodological consistency, certification awareness, and emerging digital support tools.

The novelty of this review lies in the integrated evaluation of whole-life LCA principles, certification system structures, circular economy pathways, and emerging digitalisation approaches within the context of Building Sustainability Index development. The study contributes to a clearer understanding of how methodological choices, life cycle stage coverage, and certification logic influence the robustness and comparability of sustainability assessment outcomes. Future research should focus on the development of harmonised and quantitatively comparable Building Sustainability Index methodologies integrating dynamic LCA datasets, circular economy indicators, and AI-supported assessment tools.

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