The Role of Life Cycle Sustainability Assessment (LCSA) in Reducing Carbon Footprints and Resource Efficiency in Building: A Review

Abstract

This review examines the influence of Life Cycle Sustainability Assessment (LCSA) on carbon footprint reductions and the resource efficiency of the building sector with a specific focus on its methodological limitations, integrations with digital technologies, and compatibility with circular economy tenets. This research synthesized new literature and current literature from (2010-Aug 2025) to develop a base level understanding of the current practices around LCSA and to develop some potential avenues for further research and for policy action. Our aim is to critically evaluate the extent that LCSA has transitioned from simply a conceptual framework towards a practical tool for informing sustained action in respect of sustainable construction. The results suggest the environmental assessed sustainability elements form the bulk of all reported LCSA applications, whilst it would seem that the economic and social dimensions remain largely underrepresented. There is the potential for Building Information Modelling (BIM) to underpin automated life cycle evaluations of data; however, the full integration of this has not occurred probably due to three current deficiencies: (1) ongoing data gaps, (2) continued interoperability issues and (3) an insufficiently standardized link to costs and social indicators. The need to consider circular economy principles is also a major point of omission in LCSA, as lifecycle considered for buildings needs also to account for reuse, recycling and circularity of materials over multiple lifecycles of a building. Overall, these results suggest an urgent need for methodological innovation and harmonizing. From the policy perspective, the stakes are high. The global sustainability frameworks increasingly being advocated acknowledge the need for whole life perspectives on buildings wherein LCSA provides the analytical underpinning for these frameworks. By disclosing the trade-offs across the environmental, economic, and social domains, LCSA can support the development of related policies on carbon reductions, resource efficiencies, and social equity. This potential cannot be realized unless both technological developments are complemented by adherence to governance frameworks that expect transparent, and consequently consistent and holistic assessments. In summary, LCSA is an essential methodology for sustainable building; however, it is a work in progress. By closing the existing gaps, it can be developed into a powerful agent that can influence both academic research and the global policy agenda to direct the built environment towards resilience, efficiency, and long-term sustainability.

Keywords: Life Cycle Sustainability Assessment, Building Information Modeling, Circular Economy, Triple Bottom Line, Social Life Cycle Assessment, Life Cycle Costing, Sustainable Construction, Policy Implications

1. Introduction

The construction sector is recognized for being one of the most resource-consuming and environmentally damaging industries. Construction as a sector can be blamed for a considerable share of global energy consumption, raw material extraction, and greenhouse gas (GHG) emissions. The latest estimates suggest that buildings consume nearly 40% of energy-related emissions and global resource consumption, making the building sector a vital sector for sustainability interventions (Wang et al., 2023; Berges-Alvarez et al., 2024). Addressing the impacts of buildings and construction is critical for meeting international climate targets and advancing the United Nations Sustainable Development Goals (SDGs). In the last ten years, sustainability research on buildings has transitioned to a life-cycle perspective within which the stages of the building life-cycle (e.g., material extraction, construction, operational, maintenance, and demolition stages) have been greatly expanded (Dong, 2024; Poderytė et al., 2025). This change has acknowledged that buildings and construction have environmental and

resource impacts that extend well beyond the operational impacts, and the significance of how a life-cycle perspective represents whole systems and not just one simple part as stand-alone complexities and intersections of these stories that can respond comprehensively with its methods. Life Cycle Sustainability Assessment (LCSA) has been recognized as a relevant framework for approaching this complexity. LCSA draws from the historically environmental-heavy variety of Life Cycle Assessment (LCA) to include Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) notions, to assess everyone's sustainability triple bottom line: environmental, economic, and social (Poderytė et al., 2025; Vitório, 2024). This multi-dimensionality offers an assessment of tradeoffs across different sustainability measures and provides actors with pragmatic outcomes not just about carbon reduction. Furthermore, LCSA is being increasingly associated with principles of a circular economy, towards approaches to use materials again, recycle, and waste less when applying resource efficiency (Larsen et al., 2022; Berges-Alvarez et al., 2024). Besides linking with long-term climate neutrality plans, such as the EU's 2050 strategy for net-zero buildings, LCSA also provides a systematic base for decisions on design optimizations, procuring, and drafting policy measures.

LCSA may be conceptually robust however, it faces significant challenges applying it in the building sector. Environmental impacts, particularly carbon footprints, are often assessed, but the wider social and economic contexts are also not developed in most studies (Poderytė et al., 2025; Larsen et al., 2022). This lack of completeness leads to an incomplete picture of sustainability performance and results in making holistic decision-making impossible. Add to this the issue of method inconsistency, where variation in system boundaries, allocation processes and data availability undermine the ability to compare between studies (Vitório, 2024; Larsen et al., 2022). Further, ongoing debates over the importance of embodied versus operational emissions, and how detail in methodology is necessary at early design stages, is yet another factor (Prideaux et al., 2024). These competing factors tend to affect the sustainability outcomes and add uncertainty depending on the level of detail included in LCSA as a decision-support tool for industry (Backes & Traverso, 2021; Ostojic et al., 2024).

Technology, especially Building Information Modeling (BIM), has started to ameliorate a few of these issues by improving data interoperability and allowing for dynamic, real-time analysis across the building life cycle (Ferdosi et al., 2022; Liu et al., 2023). The incorporation of BIM allows further improvement of the automation in LCA calculations, increases the consistency of data flows, and enables iterative optimization of designs (Boje et al., 2023; Ahmad et al., 2024). However, BIM and LCSA integration is still emergent with complex challenges related to software interoperability, lack of harmonized impact categories, and the integration of social sustainability indicators (Parekh & Trabucco, 2024; Akbari et al., 2024; Berges-Alvarez et al., 2024). There remains debate amongst LCA practitioners whether simplicity in LCSA is important for early design phase feasibility or if substantive and effortful LCSA methods, with high data demands, are needed for credibility and accuracy (Prideaux et al., 2024). This debate shows the important need for standardization to balance methodological integrity and practical applicability.

The conceptual framework for this review identifies LCSA as the approach of assessing the sustainability impacts of the life cycle of a building by systematically combining LCA, LCC and S-LCA for each stage of the building's life cycle, all of which can be facilitated by digital technology, to help with the management and analysis of data (Poderytė et al., 2025; Vitório, 2024). LCSA's goal can potentially provide other benefits beyond holistic sustainability assessment, particularly for future designs that seek to reduce carbon emissions, resource use, and improve positive long-term economic and social impacts. In addition, LCSA can incorporate environmental, economic, and social dimensions of sustainability that support balanced decisions particularly for a sector that is experiencing new regulations and

expectations to be sustainable, directly due to market changes (Hackenhaar et al., 2024; Brbhan & Mannheim, 2023).

There is no lack of importance in enhancing LCSA implementation in the building sector. When construction activities help shape global emissions trajectories, it is imperative to understand and evaluate design and material decisions for their life cycle impacts. Furthermore, resource scarcity and climate resilience emerge as two defining challenges of the 21st century, and LCSA provides a fully articulated and systematic pathway for the built environment to transition to circular, resource-efficient building delivery models (Salati et al., 2024). Nevertheless, to realise its potential, there remains a need to address methodological gaps, improve data availability, and support integration with digital technologies to help facilitate real-time, life cycle decision-making. The purpose of this review is to critically assess the relevance of LCSA within the context of climate change towards negative carbon footprints and resource efficiency in the building industry. By critically identifying, synthesizing research, and study of cases, this research aims at analysing how LCSA - being based on environmental, economic, and social value - offers a greater understanding and holistic answer through multiple dimensions to assess sustainability to a traditional sustainability assessment. This review will explicitly:

1. Identify the major benefits associated with adopting LCSA in building design and construction
2. Identify the methodological and practice-related barriers that hinders LCSA's implementation
3. Identify how emerging digital tools, particularly BIM, aid in implementing LCSA
4. Identify research gaps and future direction to improve the LCSA framework in the built environment.

Through its review, it addresses these aims and importantly contributes to the lifecycle-based examination of sustainable assessment methods, advocating policy, and advancing the industry to opt for more integrated life cycle-based approaches. In summary, this paper reinforces that LCSA has the potential to provide a platform upon which low-carbon, resource efficient, and socially responsible buildings can be developered to facilitate long-term sustainability in the built environment.

2. Methodology

Research Design

This study takes a systematic review approach to investigate the role of LCSA in reducing carbon footprints and improving resource efficiency in the building sector. The current systematic review method follows conventional systematic review approaches for environmental and engineering research to ensure transparency, reproducibility, and comprehensiveness.

Data Sources and Search Strategy

The literature search took place across three primary academic databases, Scopus, Web of Science, and Google Scholar, which spanned literature published from January 2010 to August 2025. These databases were chosen because they include peer-reviewed journal articles, high impact publications and conference proceedings in the area of sustainable construction and life cycle assessment.

The search terms used combinations of keywords and Boolean operators to enable the retrieval of relevant literature. The search terms were designed to include all relevant dimensions of LCSA in buildings and included terms such as:

- **“Life Cycle Sustainability Assessment” OR “LCSA” AND “building” OR “construction”**

- **“carbon footprint” AND “resource efficiency” AND “life cycle”**
- **“LCA” AND “economic” AND “social” AND “sustainability assessment”**

Filters were applied to restrict the results to English-language publications and peer-reviewed sources.

Inclusion and Exclusion Criteria

To guide relevance and quality, the following inclusion criteria were used:

- Studies that specifically discussed LCSA or integrated life cycle approaches in the context of the building or construction industry.
- Works that focussed on reducing carbon footprints, resource efficiency, or both, from a life cycle analysis perspective.
- Works that provided methodological frameworks, case studies, and empirical applications discussing LCSA.
- Works published in peer-reviewed journals or book chapters between 2010 and 2025.

The **exclusion criteria** included:

- Research outside the building domain (examples: automotive, energy systems without building relevance).
- Papers that evaluate a single dimension (examples: environmental LCA with no economic or social).
- Not written in English, editorials, conference proceedings and non-peer-reviewed works.
- Duplicate records across databases.

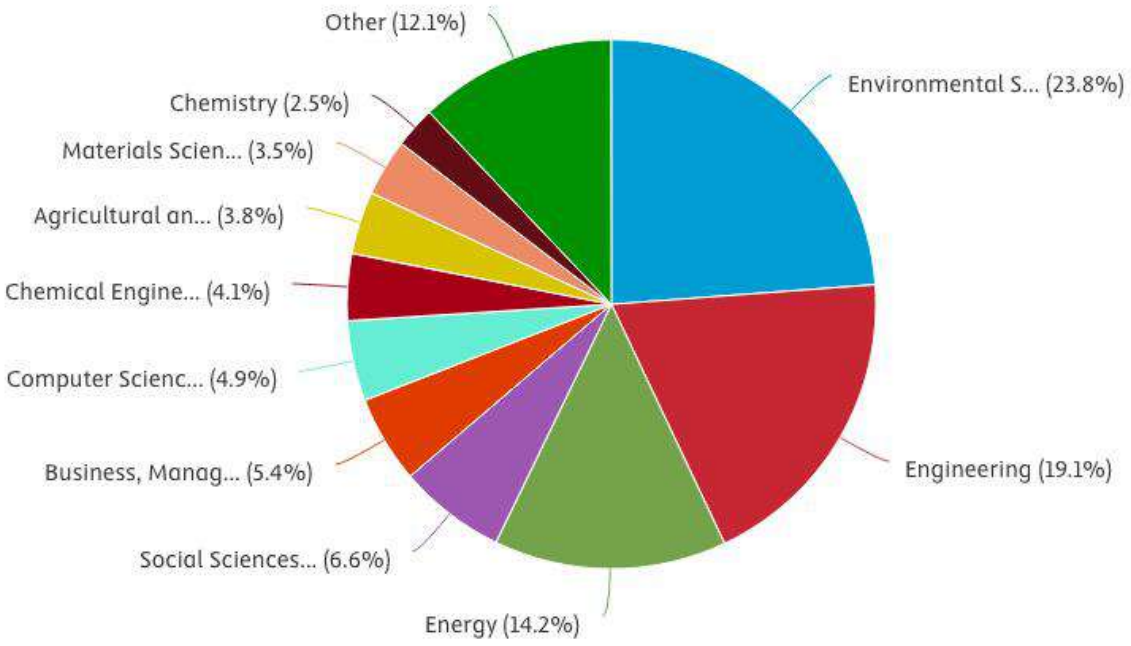

Figure 1: Subject Area Distribution

As depicted in distribution of subject areas, LCSA research, when considered through the lens of carbon reduction and resource efficiency, is largely situated in the Environmental Sciences, followed by Engineering and Energy. This exemplification of a clear environmental drive

within LCSA research exemplifies its origins in environmental impact, however, sizeable representation within Social Sciences, Business and Management and even Computer Science indicates that LCSA is moving toward a more interdisciplinary field. These recent takes reflect how the economic and social dimensions, digital technology, and decision-support systems within sustainability are strengthening, and highlight how the LCSA community is drawing itself toward holistic approaches to sustainability rather than solely technical and environmental solutions.

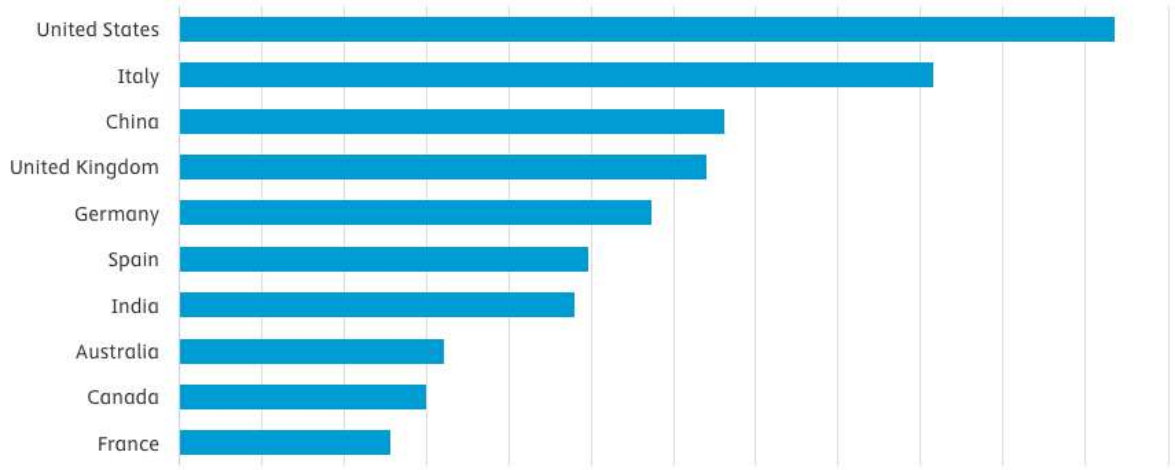

Figure 2: Country Contribution (Relative Frequency)

The geographic orientations of publications indicate that developed economies are well ahead of emerging and/or developing economies, especially the United States and Italy, but followed by China, the United Kingdom, and Germany, all of which have large economic and governmental bodies. This is not surprising, as these regions have significant research investments and regulations impacting sustainability, in part guided by climate and sustainability policies associated with the European Union and North America. Additionally, the presence of emerging economies such as India and China reveal that there is emerging awareness within rapidly urbanizing countries that have considerable construction activity and resource demand. While LCSA research may be going global, there may also be inconsistencies in research capacity and policy remodeling for LCSA implementation in practice.

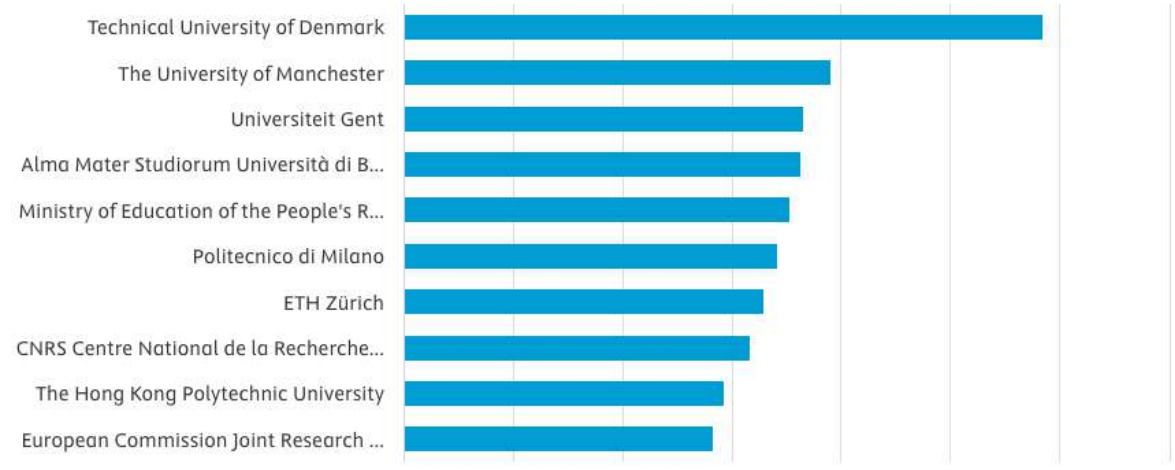

Figure 3: Institutional Contribution Relative Frequency)

A small number energy typically reflects a predominance of leading research in European universities and research organizations, with Technical University of Denmark and the University of Manchester emerging as knowledge repositories. These research universities have built up considerable expertise in sustainability assessment and digital capability for the built environment often within the confines of EU funded research grouped around the EU. The involvement of multidisciplinary centers such as the European Commission Joint Research Centre also reflects the strategic importance of LCSA for policy development. Institutional contributions from Asia, such as The Hong Kong Polytechnic University, signify the growing global outreach and collaboration in furthering methodological frameworks and digital capability for LCSA.

Screening and Selection Process

The screening process was carried out in three stages:

1. Initial Identification: All records obtained from the databases were imported into a reference manager, and duplicates were eliminated.
2. Title and Abstract Screening: Information from the titles and abstracts of records were considered to eliminate studies that were clearly irrelevant to the review (e.g. studies in unrelated sectors or those that lacked an LCSA standpoint).
3. Full-Text Review: The remaining articles were reviewed in detail to confirm relevance and rigor in method. At this point in the review process studies that only addressed a single dimension of sustainability or had minimal discussion on method were eliminated.

Data Extraction and Analysis

We created a structured data extraction form to gather key information from each study, which included:

- Publication information: Author(s), year, and journal.
- Scope and objectives: Type of LCSA application, building type.
- Methodological approach: integration of environmental, economic and social considerations; tools and software (e.g., BIM).
- Main findings: impacts on carbon footprint and resource efficiency.
- Challenges and limitations: gaps identified and future research needs.

The data extraction was thematically synthesized to identify patterns, trends and research gaps. The findings were categorized according to: methodological innovations, challenges to integration, a role for digital tools, and implications for policy.

3. Results

The reviewed studies, to facilitate an analysis of the diverse life-cycle sustainability assessment literature for the building sector, were formally grouped into nine thematic clusters. This process involved multiple iterations that began with careful reading of the studies, then coding recurrent concepts and mapping the methodological and practical emphases within the reviewed publications. The themes did not pre-exist but were developed inductively and framed dominant areas of concern in the overall literature, reflecting directions of most active research evolution. The nine thematic clusters reveal studies on methodological developments, integration of digital approaches, inclusion of circular economy principles, and regional frameworks as many possible issues of contemporary interest. The grouping of studies in a systematic way enabled a more transparent understanding of how the field has advanced in diversity, where agreements are forming, and where fragmentation and gaps in attention may be occurring, current to date. This thematic organization provides a benchmark from which to compare the relative types of attention (strengths and weaknesses) within an assessment approach, and to consider the identified gaps as important to inform future research and policy discussion.

Theme 1: Life Cycle Assessment for Carbon Footprint Reduction and Environmental Impact

LCSA has become the leading method for tackling environmental impacts in the building sector, specifically reducing carbon footprints across the building's lifecycle. Life Cycle Assessment (LCA), which considers only the environmental dimension, essentially covers cradle-to-grave material extraction, processing, construction, operation, maintenance, and demolition (Hossaini et al., 2015; Onat et al., 2014; Hernandez et al., 2019; Rashid et al., 2015; Bagley & Crawford, 2015; Kumanayake and Luo, 2018). A cradle-to-grave methodology is important because it captures the embodied energy and emissions resulting from operation and often ignored in individual phases or stages.

The prominent role of embodied energy and carbon is a common theme in LCSA research. The term 'embodied energy' describes the overall energy used from extraction, processing, manufacture, and transportation of the building materials, while 'operational emissions', represents the energy-related emissions during the use phase of the building. Many studies have found that these two factors typically have a significant impact on the whole building's carbon footprint and challenge the idea that operational emissions typically make up the majority of the environmental impacts for buildings (Hossaini et al., 2015; Rashid et al., 2015). Hernandez et al. (2019), in particular, emphasize that in high-performance buildings, embodied impacts can come close to or even exceed operational emissions over the life of a building and hence early decisions can be important.

The materials selected will greatly influence the impact of the building's life-cycle. According to Onat et al. (2014), LCSA allows users to assess material choices based on embodied carbon and energy intensities so that designers can balance performance, cost, and sustainability. Cradle-to-grave is important to ensure that low energy materials or energy-efficient technologies do not create high environmental intensity costs on their production or end-of-life costs in the operational energy consumption phase. Studies like Huang et al. (2020) and Castro & Pasanen (2019) emphasize the inclusion of the maintenance and refurbishment phases. The importance of these two phases let designers avoid total understatement of cumulative impact. The consensus of the literature supports a cradle-to-grave approach, which considers all aspects of an object's life cycle, from resource extraction to disposal (Silvestre et al., 2014). Nevertheless, some authors argue that cradle-to-cradle approaches, which put significantly more emphasis on recycling and reuse of materials, could overcome the total emissions and total resource depletion. With the parallel inclusion of circularity concepts in Life Cycle Sustainability Assessment, stakeholders will begin to modify another concept of resilience in building systems and have a more significant opportunity of achieving long-term sustainability.

LCSA provides a strong basis for making decisions with quantified environmental indicators to inform sustainable design and policy interventions. According to Bagley & Crawford (2015): LCSA outputs, including Global Warming Potential (GWP), energy demand, and other impact categories, can be used to make decisions about materials and also decisions about how to strategize building performance improvements to symbolically aid climate actions. The actual indicators provided by LCSA will help to decision-makers align building projects with climate targets or requirements imposed by certification for building green.

While LCSA methodologies have considerable strengths, challenges remain in terms of harmonization and transparency. For example, inconsistencies in system boundaries, impact categories, and data sources may yield different results that are not suitable for comparative purposes (Huang et al., 2020). As well, high-performance buildings may consider operational emissions, making it imperative that dynamic LCSA include time-sensitive energy profiles and changing energy mixes.

Theme 2: Material Selection, Resource Efficiency, and Bio-Based Solutions

Material selection is fundamental to the environmental performance of buildings across their lifecycle. Material-related decisions affect embodied energy, carbon emissions and resource depletion – the main environmental indicators in LCSA – making this area a central focus of sustainability research. In the past few decades, research has progressed from simple material efficiency in the early design stages to more complex concepts such as bio-based materials, renewable resources and circular economy-related approaches (Silvestre et al., 2014; Göswein et al., 2018; Zanghelini et al., 2018; Onat et al., 2014; Kumanayake & Luo, 2018; Hossaini et al., 2015). Early research (2010-2020) initially focused on resource optimization, and comparing the use of conventional and alternative building materials. Silvestre, et al. (2014) described that resource efficiency when constructing buildings requires a reduction in the amount of raw materials consumed, but improvement in the material's durability and maintenance properties. Kumanayake and Luo (2018) also drew attention to lightweight construction materials that can be environmentally beneficial by lowering embodied energy while maintaining structural performance. The need to develop material substitution strategies where low-impact materials can replace high-carbon materials without losing any of the functional requirements was established in our findings.

Onat et al. (2014) also included resource efficiency as part of the LCSA framework through their performance-based material selection models. Their work integrated performance metrics for environmental, cost, and functional characteristics to provide different sustainable trade-offs for designers. However, the limitation of comprehensive datasets and standardized approaches often prevented these decision-support tools from reaching broader applicability.

In the time period of 2021–2025, researchers have shifted to supporting renewable and bio-based materials as an important pathway to decarbonizing the building sector. Göswein et al. (2018) contributed to this discussion by assessing the carbon storage potential of bio-based construction materials including timber, hemp, and other plant-based composites. These studies indicate that bio-based materials reduce embodied energy and act as carbon sinks, providing a dual benefit under climate mitigation strategies. This represents a further transition from efficiencies to regenerative solutions (regenerative materials) to contribute positively to carbon balances.

Additionally, these materials are often coupled with initiatives to extend the lifetime of buildings with durability, adaptability, and circular economy principles. However, they are dependent on sustainable sourcing, manufacturing, and end-of-life considerations, all of which are still poorly defined in a rigorous way for LCSA purposes (Zanghelini et al., 2018). Another new dimension is the acknowledgement of deconstruction and subsequent reuse, as well as recycling of materials. It has been argued that early material selection should consider the deconstruction and recycling methods in order to reduce landfill or waste, and create a pathway for resource recovery. Zanghelini et al. (2018) and Göswein et al., (2018) discuss the importance of cradle-to-cradle strategies, where materials are repurposed in the economy rather than being used once. This increases resource efficiency, reduces environmental externalities, and is an important part of sustainable planning in the long run.

While it has been made significant progress, challenges exist. Bio-based materials have environmental promise, but uncertainties around long-term performance, fire performance, moisture resistance, and market adoption still exist (Göswein et al., 2018). In addition, there is little reliable life cycle inventory (LCI) data for innovative materials making LCSA model reliability difficult. Research should continue to remedy the data barriers, but also provide a practical process for incorporating dynamic performance of materials over time. Including digital tools, such as BIM, to automate material tracking and optimization will improve the utility of the material selection process in a sustainable building design.

Theme 3: Integration of Digital Tools (BIM, AI, and IoT) for LCSA and Decision Support

The incorporation of digital technologies with LCSA has introduced a new paradigm for advancing sustainable buildings. The integrated frameworks that LCSA uses have been useful, however, traditional LCSA methods have been criticized for their data-laden, time-consuming, and complex nature, which makes them less applicable when key decisions are being made earlier in the design process (Soust-Verdaguer et al., 2017; Göswein et al., 2018). One approach to this social problem has been the increasing interest in innovative research that uses BIM, Artificial Intelligence (AI), and Internet of Things (IoT) in order to develop techniques (or frameworks) that harness automation, offer greater accuracy, and real-time decision making in LCSA.

BIM is the foundational platform for integrating LCSA into building design. BIM enables centralized data storage and uses parametric modeling. Soust-Verdaguer et al. (2017) highlighted the advances being made with BIM-based LCA tools that can extract material quantities and components from digital models that reduces manual data entry mistakes and ultimately makes the environmental impact assessment a timelier process. The interoperable nature of BIM and the LCA databases allows for real-time updating of environmental indicators with design parameter changes, which opens up opportunities for iterative optimization through the design process.

AI-assisted approaches, in particular machine learning algorithms, have begun receiving attention for their ability to predict environmental performance with little or no manual modeling. Trained on large databases of types of buildings or material inventories, AI will have the ability to provide rapid carbon emissions estimative and LCSA during conceptual design stages, thereby allowing designers to make near real-time assessments of sustainability trade-offs (Kumanayake and Luo, 2018). In this context, AI allows predictive capacities to address the critical issue of early-stage decision-making. The challenge arises where, at the early design stage, LCSA methodologies are impractical due to time constraints and uncertainty in design specifications.

AI also lends itself to scenario analysis and multi-objective optimization, since it can consider a range of environmental, economic and social indicators at the same time in the context of a single consistent integrated sustainability strategy. This supports an industry shift towards a more data-driven design in conjunction with performance-based decisions with respect to resource efficiency and carbon reduction.

In addition to upstream design-phase uses, IoT technologies also offer the potential to monitor energy use, material degradation, and indoor environmental quality in building operations as live data for LCSA modeling. This feedback can in turn facilitate adaptive building operations, condition-based predictive maintenance, and validation of LCSA assumptions and assessments throughout the life of a building (Soust-Verdaguer et al., 2017). Integrating IoT data into LCSA frameworks helps to mitigate the limitations associated with static assessments in conjunction with growing operational performance in real-time context, while developing new avenues for improved accuracy and sustainability outcomes over the longer term.

Despite advances in digital connectedness, the widespread mainstream adoption of digital tools faces many challenges. These include interoperability issues between BIM platforms and LCA databases, non-standardized data formats, and high costs for implementation for small- and medium-sized enterprises. In addition, ensuring quality and transparency in AI models is essential to not create bias in sustainability predictions. Future research should explore the development of open-source digital frameworks, standardized and harmonized data protocols, and cloud-based group collaboration platforms for more equitable access to digital LCSA platforms, including coupled technological solutions to further achieve traceability and accountability in sustainability disclosures through the use of blockchain technologies.

Theme 4: Circular Economy and Multi-Life Cycle Approaches

The incorporation of Circular Economy (CE) principles into the scope of LCSA is seeing increasing interest as the built environment looks to pathways to reducing waste, resource depletion, and achieving sustainable goals in the long run. CE concepts of reuse, repair, recycling, and closed-loop system extend LCA's standard cradle-to-grave approach into cradle-to-cradle or multi-life cycle assessments, allowing for resource circularity and material valorization through the building life cycle (Eberhardt et al., 2020; Ajayi et al., 2015). This theme explores the developments towards circularity-based LCSA, their technical and practitioner challenges, and the role that approaches to combine CE and LCSA frameworks in the built environment.

Previous practices of LCA in the building sector have mainly focused on a linear approach and cradle-to-grave, perceiving each building component in isolation, and not drawing out the opportunities for material recovery or reuse at the end-of-life (Hossaini et al., 2015; Buyle et al., 2013). A shift towards circular approaches recast the perspective that the reuse and recycling of materials helps extend the useful life of materials, and the reduction of embodied carbon and extraction of resources (Carcassi et al., 2020). Multi-life cycle modeling allows stakeholders to compare and assess second-life scenarios, including the adaptive reuse of structural components, or the incorporation of recycled aggregates into new construction, moving towards net-zero carbon targets aligned with European Union policies (Gervásio et al., 2018).

Ajayi et al. (2015) note that design-for-deconstruction (DfD) and modular construction technologies are effective drivers of circularity because they enable recovery of materials without significant loss of quality. However, these approaches need to be integrated into LCSA with modelling capabilities that can take uncertainty into account in terms of material flows, recovery rates, and technological developments regarding recycling.

Although there are conceptual benefits to applying LCSA in a CE, methods-related issues still exist. A key issue of CE in LCSA relates to the allocation rules for environmental burden and credit over multiple life cycles. For example, it is not clear how to allocate the environmental impact of using recycled materials in a new building to the old and new product systems. This remains un-resolved in the literature (Eberhardt et al. 2020; Emami et al., 2019), and differences in allocation methods between studies lead to reduced comparability and decision making by stakeholders.

In addition, recycling infrastructure, energy mix, and materials flows will also differ spatially and temporally, which will add uncertainties to CE modelling (Hossaini et al., 2015). To address these complexities researchers have proposed hybrid approaches to CE modelling that combine dynamic LCSA modelling with scenario-based simulation models to account for future uncertainties in market conditions and material recovery technologies (Eberhardt et al., 2020).

Digital technologies, such as BIM, are key tools for operationalizing CE principles in LCSA. In BIM, designers can put in material passports and end-of-life information, which help to identify which elements can be reused, find optimized flows for materials, and assess the environmental consequences of circular strategies early in the design stage (Mora et al., 2020; Naneva et al., 2020). The integration of data following CE, allows for a design-for-circularity approach that systematically assesses the trade-offs between environmental advantages and economic viability.

There have been significant advances in research, yet many barriers remain that will prevent CE-based LCSA strategies form becoming mainstream in building projects. These include a lack of standardization, limited databases on secondary materials performance, and financial uncertainty associated with future material markets. Culturally, the acceptance of circular

practices such as using reclaimed materials is still limited in some regions due to a perceived lack of quality and safety (Sameer & Bringezu, 2019).
Moving forward, research should continue to develop harmonized allocation frameworks that incorporate circularity indicators versus LCSA, and potentially explore the use of digital technologies to enable material tracking and performance across multiple life cycles in real-time. Timely financial linkages between CE strategies to policy opportunities such as extended producer responsibility and material reuse credits will also be crucial in promoting greater uptake and commitment to practice.

Theme 5: Multi-Dimensional Sustainability Assessment – Environmental, Economic, and Social Integration

LCSA is distinct from conventional sustainability assessments, having a clear focus on the tripartite bottom line-over the operational life cycle of a building (Onat et al., 2014; Hernandez et al., 2019) -environmental, economic, and social. While the environmental dimension is represented and established with Life Cycle Assessment (LCA), the economic dimension can be integrated through Life Cycle Costing (LCC), however, including social implications and costs through Social Life Cycle Assessment (S-LCA) is the relatively recent research unexplored frontier for LCSA methods (Larsen et al., 2022; Vitório, 2024). This theme will address the development of multi-dimensional approaches, methodological synergies between LCA, LCC, and S-LCA, and further discuss limitations to the practical use of these complimentary assessments to the built environment.
Historically, the environmental aspect of LCSA has been the focal point of discussions, primarily because of regulatory mandates and standardized approaches like ISO 14040/44. Traditional assessments tend to deal with global warming potential (GWP) and environmental indicators (Hossaini et al., 2015; Buyle et al., 2013) like acidification and eutrophication. Some current discussions call for expanded system boundaries to account for embodied and operational impacts since both contribute significant amounts of carbon footprints of a building (Eberhardt et al., 2020; Hernandez et al., 2019). Decoupling the principles of a circular economy (Theme 4) in LCA has added to the environmental boundary, recovering materials, and addressing multiple life cycles.
Incorporating economic factors through Life Cycle Costing is a critical step to assess the financial feasibility of a product or service and its environmental performance (Backes & Traverso, 2021; Hackenhaar et al., 2024). The Life Cycle Cost accounts for the total cost of ownership, including capital costs, operation, maintenance, and end-of-life costs. The combination of LCC with LCA allows decision-makers to explore options that, although more expensive, are the most cost-effective without compromising sustainability goals. For example, project design approaches that optimize energy efficiency and material reuse were able to deliver long-term savings even though they had increased upfront costs (Boje et al., 2023). Nevertheless, some methodological aspects remain, such as those associated with discount rates, differing inflation rates, and uncertainty in future energy prices; any of those can have a substantial effect on the LCC (Poderytė et al., 2025).
The social dimension of LCSA is still the most underdeveloped and operationalizing LCSA in the social dimension is still the most challenging. Unlike environmental and economic indicators, social impacts such as worker well-being, community development, and health and safety suffer from a lack of standardized metrics and available data (Sameer & Bringezu, 2019; Vitório, 2024). Current S-LCA frameworks rely on qualitative or semi-quantitative indicators, which introduces subjectivity and limits comparability (Onat et al., 2014). Furthermore, even when region-specific data may exist, such as proxy data, these social indicators were often beyond the design stage, which introduced further challenges related to attributing a social outcome to a specific stage of the life cycle (Ajayi et al., 2015).

Hybrid modeling methods that combine stakeholder-based assessments alongside quantitative indicators concerning labor conditions, equitable resource distribution and local economic benefits are recommended (Larsen et al., 2022). The use of digital platforms (e.g., BIM) with socio-economic datasets are also being proposed as a means to systematically implement S-LCA (Ferdosi et al., 2022; Mora et al., 2020).

Although the conceptual framework of LCSA encourages blending environmental, economic, and social assessments, its practical application has been piecemeal, hampered substantially by the absence of harmonized databases that are capable of supporting all three dimensions (Poderytė et al., 2025). Furthermore, inconsistencies in context (system boundaries), functional units, and data resolution that exist between LCA, LCC, and S-LCA methodologies, inhibit and undermine comparability, ultimately harming decision making (Backes & Traverso, 2021; Vitório, 2024).

Integrating one dimension with respect to another can also be problematic so long as there's trade-off/ankle-breaking among sustainability pillars. For instance, design options that minimize carbon emissions may utilize premium materials (i.e., at a higher cost), while designs that optimize cost may intentionally select design options that enable social inequity by selecting nations that have low-cost labor and poor working conditions (Onat et al., 2014; Hertwich et al., 2019). Better approaches to instigating trade-offs should entail the use of multi-criteria decision analysis (MCDA) tools, as part of LCSA schemes that can allow developers to better evaluate competing objectives.

Involving multi-dimensional sustainability assessment requires unifying S-LCA indicators, developing interoperability between LCA, LCC, and BIM systems, and creating decision-support systems to enable a real-time trade-off analysis in the beginning stages of design (Ferdosi et al., 2022; Boje et al., 2023). Involving policy instruments, for example green procurement standards and carbon pricing, with the integration of LCSA frameworks can lead to quicker adoption across public and private sectors. Future research can also benefit from greater focus on dynamic modeling approaches incorporating socio-economic scenarios and climate uncertainties to ensure sustainability assessments remain resilient over time.

Theme 6: Dynamic and Optimization-Based Approaches in LCSA

Dynamic and optimization-based approaches in LCSA represent a nascent and very exciting area of sustainable building research. Whereas traditional static LCA techniques do not reflect temporal changes in environmental impacts (e.g., the changing energy mix, changing material supply chains, evolving embodied emissions during building refurbishments), dynamic LCA conceptually incorporates environmental impacts over time into the assessment process. In doing so, temporal changes can realistically be imbued into the life-cycle impacts of a building for the designer or decision-maker based on how material and energy use evolve over time, instead of treating it as being static (Salati et al., 2024; Kang et al., 2019). This means that scenarios such as changes to the energy mix through grid decarbonization, technology improvements, adaptive building operations (i.e., occupancy patterns), for example, would all be considered under a life-cycle sustainability analysis that is temporally sensitive. This enhances the potential for dynamic LCSA to provide useful insights for designers and decision-makers on the long-term sustainability-performance of buildings.

Optimization-oriented approaches complement dynamic LCSA and allow decision-makers to systematically explore building strategies related to design configuration, material choice, and operational practices that generate minimal environmental and economic impacts while satisfying functional and legislative constraints. Commonly used methods address tradeoffs between embodied carbon, operational energy consumption, and cost-effectiveness and include multi-objective optimization, parametric modelling, and sensitivity analysis (Shanbhag & Dixit, 2024). Related work has begun to highlight the merits of applying system dynamics and

optimization approaches to not only define the individual effects of components, materials, and energy systems and their interactions, but also make evidence-based decisions early in the design or retrofit planning (Cirrincione et al., 2024).

Integration with tools such as BIM and AI-driven predictive data models also enhances the capabilities of dynamic and optimization-oriented approaches. For example, BIM-enabled data provides both detailed inventories of materials and a description of operational parameters that can be updated as a dynamic dataset to run scenarios for a design or built environment (Boje et al., 2023; Salati et al., 2024). Similarly, AI and machine learning approaches can also project building performance in multiple scenarios, which will accelerate the identification of solutions that will result in the least lifecycle modelling impacts. These synergies allow moving towards a more adaptive and proactive approach to sustainability assessments and away from static benchmarks to predictive, performance-oriented designing.

Dynamic and continuously-optimized LCSA have many potential benefits; however, it currently faces challenges that can limit its adoption. First, the computational complexity associated with dynamic and optimization-based methods can be a significant barrier, especially when modeling large multi-component buildings, like Salati et al. (2024) addressed. Second, while we are happy to see studies employing the temporal LCA framework, single discipline LCA does not accompanying work being relegated to a specified temporal LCA approach and best practices. This creates uncertainties in definitions and parameterization, which also complicates comparisons and generates confusion for practitioners (Cirrincione et al., 2024). Finally, in the fields of architecture and design, there is currently only marginal integration with industry workflows and industry software where advanced optimization or dynamic optimization can be realized, as most practitioners neither have the expertise or ability to use the design process or tools available (Shanbhag & Dixit, 2024).

Future research directions involve developing standardized dynamic LCA frameworks, better temporal datasets, and simple software tools capable of bridging the space between advanced modeling and implementation. Additionally, broadening multi-objective optimization to include social and regulatory aspects could increase triple bottom line impacts of dynamic LCSA. Research could also consider real time monitoring and feedback loops as enabled by IoT sensors and digital twins to validate predictive models and iteratively modify sustainability assessments (Boje et al., 2023). As these challenges are addressed, dynamic and optimization-based approaches have significant potential for further developing sustainable building design and operation decisions and building policy decisions while also contributing to the transition to low-carbon and resource-efficient built environments.

Theme 7: Regional and Context-Specific LCSA Frameworks

Regional & context-specific frameworks in LCSA concepts recognize the vast impact that geographic, climate, and socio-economic contexts can have on buildings' environmental, economic, and social performance. Conventional methods for LCSA have historically been generally equipped with global data and assumptions, while they failed to capture the localized situations that have important implications for material impacts, energy performance & operations. For example, carbon intensity of electricity grids, weather conditions, material availability, and labor conditions can all modulate the lifecycle impact of buildings, and for the sake of assessment, these forms of localized impacts form an important input to sustainable decision making (Hossaini et al., 2015; Lawania & Biswas, 2018; Campioli et al., 2019).

Regional case studies (widely noted) show that targeted LCSA approaches generate implications for making informed decisions. In colder climates, operational energy drives lifecycle impacts, and therefor thermal insulation, passive design strategies, and renewable energy are vital. In tropical or temperate regions, governments' activities embodied emissions of materials will comprise much higher proportions of total impacts because there would be

less heating loads against much greater overall construction loads. The key takeaway is that both localized energy, climate, and material sourcing situation should be accounted for in the LCSA methodology for decisions with goals for improved sustainable design (Kumanayake & Luo, 2018; Hossaini et al., 2015).

Furthermore, regional and context-specific LCSA frameworks offer the opportunity to include culturally relevant social indicators and local economic realities. For example, elements of LCSA measurement such as equity in labor practice, community involvement, and health impact are sensitive to regional practices and regulatory environments. Similarly, LCSA context is sensitive to local pricing for materials, labor, and energy and can shift economic feasibility. Including these specific conditions regarding sustainability in an LCSA framework offers a comprehensive, context-oriented framework to address sustainability that can align environmental objectives and local socio-economic priorities (Lawania & Biswas, 2018; Campioli et al., 2019).

Digital tools such as BIM, GIS and digital twins can also assist with developing regional and context-specific LCSA through spatially-oriented modeling and scenario planning. The incorporation of GIS can begin to map the material supply chains, energy supplies and transportation impacts within geographic contexts. With access to regional databases for materials and climatic parameters, BIM models can also simulate energy performance and environmental impacts over time in targeted regional circumstances. Combined use of these tools can improve accuracy of information, support testing multiple scenarios, and support effective decision making based within local responsive conditions (Hossaini et al., 2015; Kumanayake & Luo, 2018).

Context-specific LCSA has some advantages, but there are many challenges to succeed. First, data gaps and inconsistencies limit accurate modeling abilities, which is particularly problematic for developing countries that face limited and outdated datasets in environmental, economic, and social aspects. Second, there are no standards for methodology; different programs have different regional assumptions which mean that it is difficult to compare results. Third, the integration of context-specific LCSA into common workflows is very complicated, requiring expertise that is often not available in practice (Lawania & Biswas, 2018; Campioli & al., 2019). To address these issues, future research should assess the potential for building localized LCSA databases; work to ensure methodological consistency for regional adaptation; and develop accessible tools that practitioners can easily apply to context-specific assessments. Moreover, research should investigate ways to incorporate environmental monitoring and predictive analytics, allowing building operations to be adjusted in real-time based on the local situation. In this way, regional and context-specific frameworks for LCSA can ultimately strengthen the meaning and application of LCSA and at the same time pursue sustainable building in a culturally and geographically relevant way that still furthers the overarching environmental goals.

Theme 8: Challenges and Barriers in LCSA Methodology and Practical Application

Even if LCSA is increasingly recognized as a holistic method for assessing the social, economic, and environmental sustainability of buildings, the real-world application of LCSA is limited by several challenges and barriers that limit the consistency of LCSA across academia and industry. One major barrier is the inconsistency in method and data. The LCA literature has variety of LCA databases, impact assessment methods, and regional assumptions that generate different results in LCSAs of similar building projects. The differences can generate ambiguity in comparison and lower confidence in the outcomes of an LCSA, resulting in limited application for designs and decisions of policies (Emami et al., 2019; Larsen et al., 2022).

The availability and quality of data are another major limitation. Environmental, economic, and social datasets for LCSA are frequently out-of-date, incomplete, or regionally biased. More specifically, social and economic indicators are under-represented and there are fewer standardized indicators to use in LCSA. These gaps make it difficult to represent the triple bottom line and hinder integrating LCSA with decision-making processes like Life Cycle Costing (LCC), and Social LCA (S-LCA) (Backes & Traverso, 2021; Poderytė et al., 2025). The situation is even worse in developing regions, where there is minimal information on local material inventories, labor data, and energy statistics, resulting in limited capacity to engage in context-specific assessments (Ostojic et al., 2024).

The final barrier to practical adoption lies in the technological and software hurdles. A number of LCSA tools require a higher level of expertise in areas of LCA modeling, data interpretation, and multi-criteria decision analysis, as an example. The workflows can be augmented by tools that integrate with BIM or other digital tools, but many of these tools often suffer from interoperability issues, lack of standardized plugins, and steep learning curves, all of which can limit their practical usage by practitioners (Berges-Alvarez et al., 2024; Chen et al., 2024). Additionally, in some cases dynamic or optimization based LCSA approaches require so much compute power that their use is impractical for long duration or multi-component projects (Salati et al., 2024).

The role of institutional and organizational factors cannot be underestimated, either. In many cases industry stakeholders perceive LCSA methods to be time intensive, resource intensive, or not sufficiently tied to their immediate cost savings or regulatory requirements. Academic research is separated from practice by limited awareness, limited training, and very little appropriate user-friendly tools or applications meeting users' operational needs (Poderytė et al., 2025; Ostojic et al., 2024). Moreover, the complexity of including multidimensional assessments of sustainability into standard design and construction workflows makes it more challenging for widespread uptake at the levels needed to make a meaningful difference in the adoption of sustainability frameworks. To tackle these challenges will require coordinated interventions at several levels. First, we need to agree and harmonise methods, impact indicators, and LCSA data bases in order to ensure comparability, transparency, and robustness. Second, working to improve the accessibility of data by establishing coherent regional inventories; ensuring accountability for improved reporting; and making availability of open access platforms can enhance both environmental and socio-economic assessments of buildings. Third, considerable progress may be achieved by developing user-friendly, integrated software tools built with modularity and interoperability employing BIM, Internet of Things (IoT) and Artificial Intelligence analytics to lessen the perceived technical burden on the practitioner.

Future research also has a role to play in realizing a bridging of the innovation of academia with the practice of industry by developing user-centric methodological guidance, creating relevant case studies, and developing capacity building programs. Focusing on real-time monitoring, dynamic assessment and predictive modelling will enhance current and future decision making and enable iterative sustainability optimizations to take place across a building's life cycle stages. If these challenges can be overcome, LCSA can move forward past a theoretical frame to create practical, industry-relevant solutions and actively work toward embedding sustainability into criteria for the construction and operations of buildings.

Theme 9: Research Landscape and Scientometric Insights on LCSA

The research environment of Life Cycle Sustainability Assessment in buildings has accelerated rapidly over the last ten years with the acceptance and usage of a more comprehensive form of sustainability assessment. Scientometric assessments show a clear pattern of development toward integrating environmental, economic, and social aspects of assessment in buildings and

a more recent expansion into carbon footprints, circular economy practices, and digital tools. Tracing research shifts enables thematic clusters to emerge as well as to highlight geographic underpinnings which can help with emerging research priorities, sharing collaborative networks, and identifying methodological needs of research (Berges-Alvarez et al., 2024; Poderytė et al., 2025).

A notable trend is the transition from an environmentally driven LCA to a multi-dimensional type of LCSA with LCC and S-LCA. Supporting evidence shows that environmental assessments often emerge as primary, but economic and social aspects are beginning to emerge through multi-criteria decision making, stakeholder engagement, and policy- -based evaluations. Scientometric assessments also show that interdisciplinary, linking, civil \ engineering, architecture, and environmental science is a burgeoning growth area that leads to improved and more compelling sustainability assessments (Ahmad et al., 2024; Vitório, 2024).

Another developing realm of artificial intelligence (AI), BIM, Internet of Things (IoT), and digital twins is the potential enhancement of data collection, modeling, and scenario analysis strategies. Scientometric mapping indicates that the volume and variety of publications investigating BIM-LCA integration is increasing, and research attention is shifting toward automating the management of material inventories, improving data accuracy, and assembling "live" impact assessment. The rising number of digital LCSA studies also supports the idea that sufficient consensus is building around a growing understanding of the importance of real-time, predictive modeling and optimization in terms of sustainable building design and operation. (Boje et al., 2023; Keyhani et al., 2024).

Scientometrics also provides regional analysis, revealing global trends. LCSA studies produced in Europe and North America were key, particularly in terms of methodological development and methodological application in case studies. The COVID-19 pandemic provided opportunity for more countries from Asia, Oceania and South America to initiate LCSA studies, and this constitutes a net gain in importance of the sustainability assessment framework developing in a broad international manner. LCSA in various guises is quite common and this adaptation to context, including climate, material situations, and how to construct buildings (Akbari et al., 2024; Poderytė et al., 2025).

While an increasing body of literature exists, a multitude of research gaps remain. Scientometric research found little standardization of LCSA methods, varied reporting of data, and a lack of social and economic indicators. A similar review comparing academic and industry frameworks found these communities have fallen short of achieving common understanding and showed, even in the face of rapid academic progress, the practical adoption of LCSA is sporadic. Repeating LCSA studies in their original context, and collaborative resources such as media, common databases, and protocols may enhance theoretical LCSA research (Berges-Alvarez et al., 2024; Poderytė et al., 2025). Research could focus on breaking down methods to establish consistency, establishing social and economic indicators, expanding regional datasets and reference points that will help in context specific analysis. Greater collaboration between academia, industry, and policy could close the research-practice gap and offer actionable practices within the built design for sustainability. The integration of new digital technologies and LCSA — AI and emerging predictive models, e.g., integrating LCSA with real time monitoring — to further cause innovation and ease of practice for operational efficiency. Addressing these concepts will support evolving the research environment into a more acceptable global, relevant, and practical LCSA.

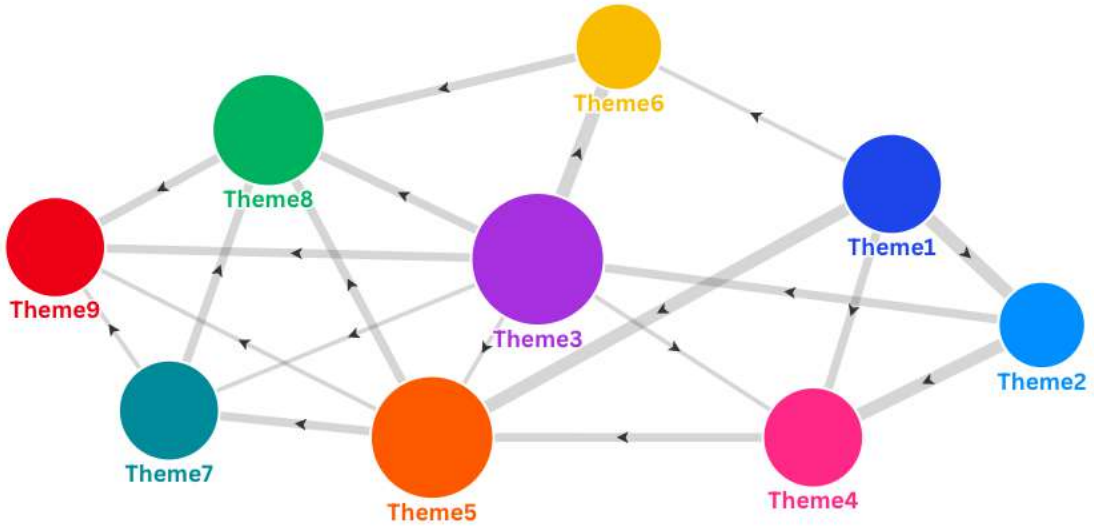

Figure 4: Network Analysis of Key Themes in LCSA

The network analysis graph illustrates networks among nine primary themes within LCSA to reduce carbon footprints and improve resource efficiency within buildings. Theme 3—Integration of Digital Tools (BIM, AI, and IoT) for LCSA and Decision Support—emerges as the focal point and the primary node with a degree of 7 appearing to tie extensively to Theme 6 (Dynamic and Optimization-Based Approaches) and Theme 8 (Challenges and Barriers in LCSA); the graphical network analysis shows how technology eliminates methodological voids and provides flexibility to the evaluation. Theme 5—Multi-Dimensional Sustainability Assessment (Environmental, Economic, and Social Integration)—with a degree of 6, connects chiefly to Theme 1 (Life Cycle Assessment for Carbon Footprint Reduction) and Theme 4 (Circular Economy and Multi-Life Cycle Approaches) demonstrating how these frameworks can enhance circularity and the benefits for the environment. Themes on the periphery, such as Theme 2 (Material Selection and Resource Efficiency) to Theme 4, showcases the innovations in sustainable materials, while Theme 9 (Research Landscape and Scientometric Insights) to Theme 8 points to developing academics attempting to resolve implementation challenges. Overall, we can see that the structure of the clustering illustrates that digital tools and multi-dimensional tools act synergistically to move LCSA towards sustainably effective building practices.

5. Gap analysis

Full Integration of Triple Bottom Line in BIM-LCSA

The complete integration of the triple bottom line—with environmental, economic, and social dimensions—into frameworks for BIM-LCSA represents a significant research gap. This gap exists mostly because existing frameworks tend to rely on some combination of environmental impacts and economic and social aspects as secondary or separate elements of assessments. In practice, this limited integration (or consideration of elements) results in incomplete sustainability assessment, which conceives these pillars as independent rather than interdependent aspects, resulting in decisions that do not consider possible tradeoffs, such as costs and the potential for socioeconomic inequities in building occupancy and their effects on communities. For instance, in the absence of simultaneous assessments, BIM-LCSA tools cannot effectively model constructions where environmental favors (such as energy-saving materials) increase initial costs in ways that are disproportionate to those who are low-income stakeholders and in doing so undermine ambitions for holistic sustainability modelled using

BIM-LCSA tools. This concern is compounded by LCA's historical focus on environmental issues, leaving social and economic dimensions of integrated models on the back burner until robust environmental assessments develop, leading to technically sound assessments which we can see are less robust in terms of the socio-economic aspects of assessments. Therefore, recent evidence from a number of studies confirm this limitation and if we think about the lack of a tripple bottom line through the practical use of BIM-LCSA tools the social and economic aspects of sustainability remain underdeveloped in number of studies as well (Berges-Alvarez et al., 2024; Larsen et al., 2022; Boje et al., 2023). In addition, scores of studies continue to also even further emphasize environmental and economic dimensions of sustainability while social sustainability arguably continues to hang out, while social sustainability seemingly continues to diminish or slight sustainability credibly across sustainability's purported tripple bottom line impacts of building projects (Onat et al., 2014; Ding, 2014; Hernandez et al., 2019; Backes & Traverso, 2021; Bíró & Csete, 2023).

Standardization and Interoperability of BIM-LCSA Tools

The issue of standardization and interoperability in BIM-LCSA tools represents a significant research gap, since there are no standard data exchange mechanisms or interfaces/maps to link BIM software ideally to LCA tools, which is subsequently splitting despite the best intentions and generally making processes more complex. From an analytical perspective, as standardization is lacking, data flow is limited, but so is the completeness of assessment and the consistency of the outcomes of assessment ultimately because every assessment that is using varied formats and interfaces is forcing the user to rely on either a manual input, or custom scripts, raising incidences of error and wasted time. If used in a building context with a multidisciplinary team across design, construction and operations, the likelihood of incongruent sustainable development metrics, may not only prevent the adoption of LCSA as an example of SD for carbon footprint impact and the optimization of resources.

Further, the lack of standard benchmarks makes cross comparisons across projects untrustworthy, ferments silos in industry practice and delays advancement towards integrated digital ecosystems. The literature surrounding the inconsistent interoperability, firstly, has shown fragmented processes, and limited practical uptake of BIM-LCSA, despite clear benefits in its use of evidence, that support improved sustainability assessments (Parekh & Trabucco, 2024; Chen et al., 2024; Seano, 2024). This can be largely linked to methodological inconsistencies both in system boundaries and impact categories (Rashid et al., 2015; Tecchio et al., 2019; Ding, 2014; Berges-Alvarez et al., 2024; Mercan et al., 2024; Poderytė et al., 2025; 2022; Gervásio et al., 2018; Emami et al., 2019) - reducing comparability and replicability across projects.

Social Life Cycle Assessment (S-LCA) Maturity and Indicators

The immaturity of Social Life Cycle Assessment (S-LCA) and availability of bespoke indicators is a significant gap in LCSA research because S-LCA methodologies are still immature and there are no reliable and robust metrics related to specific buildings to quantify social impacts such as worker welfare, community health, and equity across the building lifecycle. This mismatch leads to unbalanced sustainability assessments where the social pillar is either relegated to a lower importance or assessed using non-validated generic indicators that oversimplify the urban complexity from a social-culture perspective. For example, the implications of how building material sourcing may relate to local labor conditions, or how building design features may have ramifications on the well-being of building occupants, are compromised when mature S-LCA tools do not exist. Therefore, there is a risk that existing social blind spots can reinforce community disadvantages or inequalities, while undermining the overall impact of sustainability efforts. The gap occurs because environmental LCA has historically monopolized the LCA attendance schemes. We will need to explore ways to generate interdisciplinary approaches, introducing sociology and ethics to LCSA analyses in

the academic, institutional, and implementation functions as illustrated in previous works. The empirical evidence indicates that social sustainability routinely influences LCSA analyses but falls short or becomes ineffective, diminishing the message of the triple bottom line and limits practical judgement in building contexts (Larsen et al., 2022; Vitório, 2024; Bíró & Csete, 2023; Berges-Alvarez et al., 2024; Backes & Traverso, 2021). Furthermore, the inconsistent engagement of social considerations, in a broader LCSA effort, suggest that more quantitative references will be required to understand trade-offs, and the nuances between building sustainability and social sustainability (Onat et al., 2014; Hernandez et al., 2019).

Data Quality, Availability, and Regional Variability

Data quality, data availability, and variation by region are a chronic research gap in LCSA which is evidenced by inconsistent, incomplete, or geographically skewed databases, as well as environmental product declarations (EPDs), that create inaccuracy and limit comparability of sustainability assessments for the construction sector. Poor quality of data contaminates models irreparably, and generates uncertainty in results. Consequently, users can often misestimate the material impacts, or lifecycle emissions by considerable amounts, and when variability exists between regions in terms of manufacturing and waste management, this can compound issues of misestimation. For instance, if a user employed generic global life cycle databases, the carbon footprints of materials sourced from developing countries were likely overstated because the local efficiencies that exist, would not have been considered; while the foot prints of materials from a region that has far more restrictive regulations, would have been understated. Similarly, this misestimation further complicates comparison benchmarking or policy advice for a system that is geographically removed from the assessment. In addition, the issue of "regional variability" is part of the research gap, where data are not representative of the context of regions less representative of industrial scale. In other words, the empirical research base that creates value for theory does not extend to the generalizability of the specific region's context, complexities in material inputs and outcomes means that the researcher's interests also do not extend globally or regionally.

This gap emerges from the overall fragmented data collection ecosystems that inhibit the sharing and conjugate databases for the purpose of open access. Some literature suggests that data gaps and missing data diminish the confidence in the output of LCSA (Life Cycle Sustainability Assessment), which ultimately diminishes the accuracy of primary materials and circular economy steps (Mercan et al., 2024; Röck et al., 2024; Hackenhaar et al., 2024; Berges-Alvarez et al., 2024; Modolo et al., 2022). In addition to the LCA data limitations, other variation in the existing databases along with biases toward developed contexts increase the numerical variation related to impact assessments which, become prevalent when assessing for reliability as it related to decision making (Crawford et al., 2019; Ajayi et al., 2015; Emami et al., 2019; Lawania & Biswas, 2018; Ding, 2014; Vitório, 2024; Poderytė et al., 2025).

Practical Usability and Industry Adoption Barriers

The research on BIM-LCSA also involves practical usability and barriers to industry adoption, suggesting a significant gap in this field of study, where complexity, time constraints, and no user-friendly tools make it difficult to incorporate BIM-LCSA into typical building workflows, thereby separating academic knowledge from business reality. From an analytical aspect, this usability gap represents a learning threshold and resource-intensive process, which disassociates users from experiencing adequate usability individually, such as when relying on architects or contractors to utilize BIM-LCSA, and underutilizing BIM-LCSA for near real-time sustainability feedback/analyzing sustainability alternatives to more accurately obtain the carbon footprint for building materials whilst continuing to use traditional assessments. From an analytical perspective, the barriers do not only relate to Technical issues, they also include Institutional (organization) barriers, such as culture/resistance, lack of training/expertise, engagement resistance, lack of incentives, all of which slow down the diffusion of sustainable

practices in the built environment, and do not allow for the greatest opportunity to reduce carbon emissions. This gap is apparent because the academic community has become overly focused on complex models, with an increasing disconnect from the needs of practitioners, and efforts will need to be made toward user-centered design to close this gap. Studies show that models based on solid theory, and nevertheless have created complex models and models with readiness gaps, have become burdensome for practitioners (Berges-Alvarez et al., 2024; Ostojic et al., 2024; Larsen et al., 2022; Backes & Traverso, 2021; Prideaux et al., 2024). Considering the disconnect between the academic and industrial community surrounding readiness gaps, we've built complex models that do not translate to tools thereby continuing to disrupt the transition to sustainable practice in projects (Ostojic et al., 2024; Prideaux et al., 2024).

Dynamic and Temporal LCSA Methodologies

Dynamic and temporal approaches in LCSA are severely underdeveloped, which means that traditional static models have been blind to changes in energy use, carbon emissions, and technological advances throughout the long-term life-span of buildings, and thereby have produced assessments that do not hisrorically represent ongoing realities. From an analytical perspective, the absence of temporal dynamics in conventional approaches means that time dependent variables such as changing energy grids and energy use patterns toward renewables, or changing the impacts of climate in our operational requirements, are not incorporated, resulting in overly optimistic or pessimistic projections that ultimately misallocate investment in low carbon options. In a building life cycle exceeding decades, ignoring temporal dynamics can undervalue designs that are adaptive, such as incorporating future-proof materials, and may emphasize initial impacts too much by neglecting the value of post-construction changes and/or adaptations, thus producing inaccurate estimates of resource efficiency. This constraint originates from the computational limitations of early LCA tools which traded realism for simplicity and speed of assessment, however, it is now a necessity to integrate this first change with some form of predictive modeling to improve overall foresight. Research has proven that failure to account for temporal changes diminishes the relevant and reliable meaning for assessments provided by traditional methods (Salati et al., 2024; Shanbhag & Dixit, 2024; Yeung et al., 2023; Kang et al., 2019; Carcassi et al., 2020).

Integration of Emerging Digital Technologies (AI, IoT, Digital Twins)

Integrating emerging digital technologies (e.g. Artificial Intelligence [AI], Internet of Things [IoT], and digital twins) into LCSA frameworks is an emerging gap - but one that is poorly explored. Unlike Healthcare, which has traditional and standardized processes for conducting real-time monitoring and evaluation, LCSA frameworks and assessments do not have formalized processes. Consequently, we do not even have the empirical basis or standardized protocols for examining a significant gap in the market for dynamic, real-time sustainability monitoring and evaluation in buildings. To ground this analysis, we could be taking advantage of the potential of AI for predictive analytics on lifecycle impacts or leveraging IoT for real-time data identification during a building's operational stage. Right now, each assessment is based on a static baseline and lacks opportunities to identify the real-time adaptive optimizations "on a second-by-second basis" to reduce waste and resources. While digital twins simulate building performance, there are still significant integration hurdles, such as data privacy and security concerns, computational processing, and applicable interoperability standards. Hence, we may need to assess any potential breakage as self-contained and purposed designs and applications that are less transferable and scalable. Therefore, this gap demonstrates the limitations of traditional methods keeping up with technology, which need to be rigorously probed to gauge any potential benefits, such as increased accuracy in tracking carbon impacts. There are indications in the literature that both AI and data collection technologies are well-suited to incorporating responsive systems; however, the level of initial

integration of these technologies still requires dealing with data and computational issues (Highmore, 2022; Boje et al., 2023; Cerchione et al., 2024).

Optimization Techniques in LCSA

Fragmentation and a largely theoretical focus characterize optimization approaches in LCSA. This creates a gap where various approaches to trade-off the environmental, economic, and social objectives are imperfect, can be inconsistent, and do not have established protocols to test them meaningfully to inform, and constrain the employability for sustainability-based decisions. Analytically, LCSA users have difficulty with multi-objective trade-offs. For example, an installation may have minimum embodied carbon and be economically viable. When the LCSA is provided in a normative optimization framework, the users rely on heuristic approaches simply because it is not computationally possible to test all reasonable options quickly and an algorithm may produce different outcomes from the prior. LCSA with no optimization framework renders a skewed allocation of resources where the design stage would ideally have employed a computational efficiency model for options selections using advanced methods (genetic algorithms, and / or machine learning, etc.) but was constrained to a heuristic-based approach because the options used to base the constraints was in disregard of the previous collective decisions. The predominate attention to using LCSA with theory stems from academics exploring areas not regulated by industry frontiers. The gap can only be realized through control-sample case-study-revisions. The literature suggests that the various forms of optimization techniques are indeed diverse yet computationally excessive and not methodologically addressing the parameters of interest (Cirrincione et al., 2024; Cerchione et al., 2024; Čuláková et al., 2013; Ganjidoost, 2011).

Circular Economy Integration in LCSA

Circular economy integration is not addressed holistically in LCSA leading to a gap and key aspects like reuse of materials, recycling, and service life extension are left undercounted and inadequately addressed limiting complete assessments of resource efficiency and carbon abatement across built environment lifecycles. Analytically, this absence of acknowledgement means that multi-lifecycle impacts are not accounted for when using linear models (which do not have all the benefits attributed to the lifecycle) and may undervalue circular benefits, such as embodied emissions that are reduced as a result of remanufacturing, and perhaps worse, encouragement of designs that favour disposability. As an example, if there are no proper allocation methods to share benefits across cyclical cycles, LCSA would be disincentivized to pursue designs that facilitate disassembly risking potential resource depletion in an industry that relies on a non-renewable resource. The absence of circular economy issues presents a gap in traditionally sustainable cradle-to-grave LCA maintaining a linear nature which is contradictory to a circular sense requiring new metrics of circularity. We have shown through this study that neglect of these aspects restricts the ability to encourage sustainable behaviour and assess resource recovery. (Larsen et al., 2022; Xue et al., 2021; Hackenhaar et al., 2024; Eberhardt et al., 2020; Hossain & Ng, 2019; Castro & Pasanen, 2019; Silvestre et al., 2014; Pierucci, 2015; Ortiz et al., 2010).

Geographic and Contextual Bias

Geographic and contextual bias of LCSA studies is a significant gap with LCSA studies over-whelmingly located in developed countries, in certain climatic zones and therefore limit the external validity and generalizability of the study's findings to different global contexts. And analytically, it creates systematic errors whereby assumptions based on temperate and high income, temperate countries around consumption or material access might have little to do with tropical or low-income contexts and produces inaccurate carbon footprint estimates and resource efficiency strategies. For example, studies from Western Europe make significantly inaccurate assumptions regarding impacts in arid areas based on water scarcity personified as environmental burden and non-consideration of socio-economic assumptions such as the

existence of informal labour in some development market conditions which limit the inclusivity of the sustainability framework. This limitation is a consequence of differences in funding availability, and data availability creating a narrow world view that limits equitable global applications. Studies confirm that geographic concentrations similarly limit applicability to different environmental and socio-economic contexts (Hossaini et al., 2015; Lawania & Biswas, 2018; Kumanayake & Luo, 2018; Vitório, 2024; Mercan et al., 2024; Poderytė et al., 2025).

Early-Stage Focus and Data Granularity

The focus of LCSA on early-stage applications combined with low levels of granularity creates a gap where assessments that support early-stage decisions rely on coarse, aggregated data. Uncertainty introduced when the granularity is limited undermines the reliability of sustainability decisions. Low granularity limits the analytical capability to capture fine-grained variables such as material compositions or site-specific conditions, resulting in high level approximations of variables that may ignore high impact possibilities to reduce carbon through material substitutions, for example. If 80% of a product/program life cycle impacts are determined in early design phases, a lack of detailed information will propagate uncertainty downstream of the design process and jeopardize the design quality in terms of how the product or program will operate or be dealt with at the end of life. This lack of granularity gap originates from limited data existing for hypothetical solutions in the early conceptual phase, and therefore might require more advanced estimation methods to get to a level of accuracy. Understanding the way that the early-stage focus combined with low granularity means that each element creates inaccuracy and effectively undermines decision support of designers and managers. (Soust-Verdaguer et al., 2022; Prideaux et al., 2024; Naneva et al., 2020; Crawford & Bunster, 2020; Castro & Pasanen, 2019).

Narrow System Boundaries and Phase Emphasis

Limited system boundaries, and/or disproportionate attention to certain lifecycle phases, especially operational energy, is a significant limitation within LCSA. If missed lifecycle stages, such as maintenance, end-of-life, and/or localized considerations are excluded from sustainability assessments, carbon footprints may be misrepresented; therefore, limiting sustainability frameworks. Furthermore, if all the embodied emissions tied to construction or waste disposal is neglected, it may overshadow the effort to increase resource efficiency analytical assessments, as operational optimizations could simply hide higher costs upstream. If this is the case, instead of a sustainable approach, more often than not the results will trigger the linear economies to use a higher impact material, resulting in increased carbon footprints (e.g. if the operational phase receives a higher focus by excluding every aspect linked to the construction phase, it may justify using a material that are higher impact and associated with energy requirements). Ultimately, boundaries are a methodological boundary that's convenient, but also limits the completeness of research in research areas that are fundamentally dependent on full-cycle perspectives. There is evidence to suggest that narrow boundaries and disproportionate attention given between life-cycle assessments compromises completeness of assessment outcomes and gives rise to potentially misles strategies for mitigation (Hossain & Ng, 2019, Rashid et al., 2015, Ding, 2014, Buyle et al., 2013, Ajayi et al., 2015).

Small Sample Sizes and Case Studies

Small sample sizes and limited case studies in LCSA research create a limiting gap when the studies are often derived from narrow sets of building typologies or contexts. LCSA process may miss the necessary variability of materials, designs, and environmental conditions to make more generalizable inferences. Specifically, this relative lack of methodological scope is analytically problematic because it often primarily reduces statistical power and increases the odds of overfitting to certain scenarios - resulting in findings that may not be representative or applicable to unique building portfolios, even as broad as from residential to industrial structures. For example, a key LCSA study for a high-rise building in a temperate climate may misrepresent the same LCSA for low-rise buildings in less temperate climates (e.g., humidity tropics) due to just not accounting for context sometimes significantly influencing LCA carbon footprints, and overall resource use, etc. There is a gap in LCSA research due to an uncertain level of empirical resource limitations that always sufficiently limits the amount of data research could generate through breadth depth. The need for sufficient sample sizes to compare and contrast more generalizable datasets is apparent including using environmental impact tools with more dataset datasets with sufficiently large numbers. Studies have demonstrated that limitations or scope restrictions on sample sizes limits the variability and overall applicability of the results (e.g couple of case studies) (Hossaini et al., 2015; Lawania & Biswas, 2018; Emami et al., 2019).

LCSA Tool Reliability and Database Transparency

LCSA tool reliability and database transparency suffer from inconsistencies and a lack of high-level benchmarking to fill the void between methods and data that produce the substantial differences in outcomes that have resulted in uncomparable conclusions and a loss of general trust in sustainability assessments for buildings. analytically, the non-transparent databases with their hidden assumptions, such as emission factors and other regional specifics, lead to different results that baffle users and make it difficult to apply either policy or design consistency. For example, truly different interpretations of the same material data have been observed in different tools and it is not unusual to see 20-50% differences in carbon estimates, complicating discussions about trade-offs, and affecting the general application of more reliable LCSA practices. The proprietary nature of many of these databases, and the frequency of their updates, meaning that transparency will need to be facilitated. With the direction of research recognizing that substantial inconsistencies and a lack of validation place uncertainties both reliability and comparability needed for informed sustainability decision-making (Menzies & Mirzaie, 2016; Emami et al., 2019)

5. Discussion

Life cycle sustainability assessment has emerged as an important framework for assessing sustainability in the built environment. LCSA incorporates environmental, economic, and social dimensions into a comprehensive perspective used to assess sustainability. From a practical perspective, however, the built environment still largely favours environmental measurements in terms of energy use and carbon emissions; the dimensions of economics and social sustainability do not have consistency in addressing aspects relevant to sustainability. While there are a number of global strategies and policy frameworks with discussions of the role of buildings, their significance in the wider context of sustainability goals, action, and outcomes is still limited. Similarly, the tools and practices the built environment industry use for sustainability assessment remain somewhat disconnected and partial. LCSA is conceptually necessary, yet the move to practice is still evolving.

Digitization is often framed as an enabler of LCSA, but it has yet to reach its full potential. Building Information Modeling (BIM) has been suggested as an ideal instrument to automate data collection to provide shared information models capable of life-cycle analysis.

Theoretically, BIM could allow for real-time sustainability assessments to be conducted across the entire lifecycle of a building, informing earlier decision-making about design. Nevertheless, there are gaps. Current workflows still suffer from limited interoperability, restricting data sharing across platforms, a lack of available data, and following structures for linking BIM objects to relevant environmental, cost and social datasets. In particular, the social sustainability indicators are rarely embedded into digital spaces. As such, LCSA applications utilizing BIM are still largely limited to later stages of the design process or of compliance, rather than act as proactive design-supporting tools. Moving forward however, it is clear that harmonized data standards, integrated databases, and automated connections between BIM and sustainability parameters need to be created to transform these digital systems into viable life-cycle assessment tools.

A key challenge in implementing LCSA is balancing environmental, economic, and social issues. Environmental assessment is the most developed component; however cost and social issues tend to be fragmented. Life cycle costing requires consideration of long-term investment, maintenance, and externalities, whereas social life cycle assessment requires data on labor rights, health, safety, and community effects. These conditions are complicated and exacerbated by the lack of standardization and consistent data. Additionally, trade-offs across sustainability dimensions are rarely represented holistically. Developing integrative methods that incorporate quantitative and qualitative considerations is still a priority for LCSA. Some examples include multi-dimensional approaches, dynamic costs, and better conceptual frameworks for social indicators. Until we can develop comprehensive understanding of LCSA as a holistic balance decision tool, the environment will suffer.

The perceived increasing focus on circular economy principles deepens the conversation. Buildings are long-lived physical assets, and decisions about design, materials, and end-of-life options impact a number of resource flows for decades. Following the principles of cradle-to-grave from traditional life cycle assessment, we still need to evolve life cycle assessment to look more broadly at reuse, recycling, and material loops.

Recently, frameworks have been established that extend LCSA, and incorporate indicators for circularity by including factors that capture product longevity and recirculation of materials. This is key to aligning assessment practices with the global ambitions of resource efficiency and waste reduction. However, adding circularity to life cycle sustainability assessment presents a specific methodological challenge when assessing the environmental, social, and economic impacts of a built environment.

For example, instead of just one use-cycle at the end of life of a building, we will need to consider the impacts of multiple use-cycles of a building (therefore possibly changing the boundaries of the system). This raises many questions as there could be trade-offs to assess in this analysis regarding circular strategies against social or economic related impacts. Thus, the application of circularity metrics to life cycle sustainability assessment is an exciting but emerging topic that needs to be clearly defined through methodology and consensus.

Research and practice in LCSA have a strong implication for global policy. Global drivers and frameworks, including sustainable development and climate action, are adopting a whole-life method of looking at buildings more consistently. LCSA is providing the information policymakers need to make these frameworks relevant to building practitioners by revealing the hidden impacts of supply chain, embodied, and operational energy and impacts, and making long-term economic and social impacts visible. Policymakers can grow the range of potential to respond to their climate agendas, equity agendas, and resource efficiency agendas (which can be a very wide subject) by drawing upon the insights from LCSA. Examples of this attention to lifecycle-based reporting requirements on public construction projects, benchmarks for embodied carbon, and processes which would transfer risk to the contractors and suppliers based on an all emissions account of compliance, which brought more risk and moved towards

LCSA thinking. The barriers to putting into practice what we referred to in our research—as international barriers in our adoption of LCSA (i.e., the uncertainty around methods and standards, poor data coverage and accounting of 'social' impacts)—are mirrored in the barriers which national policymakers encounter when seeking to embed sustainability in future regulation. When policymakers attempt to encapture all aspects of their sustainability requirement agenda (carbon neutrality, equity, resource efficiency) they face the same uncertainty over accounting for carbon emissions (and their lifecycle), sustainable materials, and acceptable social impact metrics. Progressing strategic and collective understanding will depend on the timing of further developing LCSA in consideration of the appropriate link to policy frameworks which ensure that data can become available to practitioners on a basis of transparency, comparability and accountability throughout our built industry.

6. Conclusion

In summary, LCSA provides a platform from which to further sustainability in the built environment. It connects the present and the future by allowing design teams to be responsible in their short-term decisions by understanding their influence on climate, resources and society over the long-term. As it currently stands, there is a strong conceptual foundation for LCSA, but there is both dislocation in practice and it has primarily been influenced by environmental considerations, leaving social and economic impacts behind. Perspectives like circular economy and digitalization provide significant rooms for growth, but equally identify also the need for standardization and interoperability while undertaking innovative steps forward in method. In respect of policy, LCSA can be used as both a tool and a strategic approach: it allows for evidence-based decision-making, it establishes decision-making trade-offs and it builds pathways for sustainability within everyday practice in building. As methodological challenges are systematically reduced, LCSA has the potential to become an anchor for global sustainable construction strategies, to support research and governance for transition towards a more resilient and fairer built environment.

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