

Review

A Systematic Literature Review for the Development of a Consolidated Method for DLCA

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Academic Editor: Angel Mena-Nieto

Recent Prog Sci Eng

2025, volume 1, issue 3

doi:10.21926/rpse.2503014

Received: May 28, 2025

Accepted: September 12, 2025

Published: September 23, 2025

Abstract

Dynamic Life Cycle Assessment (DLCA) is an emerging approach in the construction industry it is. Yet, current research is often limited, overlooks operational patterns, and relies on generic case studies, highlighting the need for an extended method to apply these analyses in the built environment. This study conducts a Systematic Literature Review to evaluate the current state of DLCA research and identify key steps toward developing a unified and globally applicable methodology. Using the PRISMA protocol, 69 peer-reviewed articles were selected and analyzed through bibliometric and bibliographic methods. The findings were organized using a SWOT (Strengths, Weaknesses, Opportunities, and Challenges) framework. Results show that DLCA remains a growing area of interest, with consistent publication rates and leadership from developed countries and main publication vehicles. The integration of Industry 4.0 technologies presents promising opportunities for enhancing DLCA through real-time data management and richer databases. However, challenges such as high



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implementation costs, limited training, and stakeholder resistance persist. This study contributes by summarizing in an organized form the current trends and barriers, offering insights to support the development of standardized DLCA practices and informing future public policies aimed at environmental protection and sustainable construction.

Keywords

Dynamic life cycle assessment; DLCA; LCA; bibliometric analysis; temporal life cycle assessment; bibliographic analysis; time-dependent variables

1. Introduction

Based on the foundations of [1], it is possible to describe Dynamic Life Cycle Analysis (LCA) as an approach that explicitly incorporates dynamic process modeling, considering temporal and spatial variations. The application of these analyses is more common in industrial manufacturing contexts, but in the construction industry, there are few cases of implementation of these analyses [2].

Each building has its own input and output characteristics (resources consumed and pollutants emitted), which vary considerably between different structures [3, 4]. Furthermore, the life cycle of a building is generally much longer than that of other products, and the operational process can change over time [5]. This implies that dynamic factors have a more prolonged and complex influence on the assessment results, making it necessary to develop a building-specific DLCA model, considering the various complex processes and activities involved.

Currently, the LCA process is static, mainly in the construction industry. This results in limitations in the development of specific criteria and indicators to assess the sustainability of buildings from a dynamic perspective. These criteria have limited opportunities for improvement and adaptation to changing market characteristics, in addition to ignoring the effects of variations in environmental impact over long periods [6, 7]. There is also a tendency for the few Dynamic Life Cycle Analysis models available for buildings to focus more on dynamic economic parameters, ignoring the influence of dynamic environmental and occupancy behaviors [5].

Finally, it is worth highlighting that the existing DLCA models were developed with generic analyses of the construction industry, which makes it impossible to apply them directly to all products in this industry (buildings, infrastructure works, etc.), since resource consumption patterns, their function and their interface with users vary significantly between projects, countries and regions, and in the context of each one [5, 8-11].

It is understood that with the advancement of technology and digital tools applied in civil construction [12, 13], the possibility arises of integrating DLCA with innovative and sustainable construction approaches that use 4.0 technology to offer techniques and procedures that improve the life cycle assessment of buildings [5, 14]. However, despite the emergence of Industry 4.0 technologies, such as low-cost sensors, data transfer via the Internet of Things (IoT), cloud processing and storage, among others, which offer the potential for more efficient and real-time data collection and analysis, there is low implementation of the correct DLCA in buildings [15, 16].

Considering this general scenario, existing dynamic assessment models appear to be incomplete and struggle to provide accurate results and mitigate environmental impacts during the operational

phase [17, 18]. They appear unsuitable for application in buildings due to the uniqueness of each project and their long service life [19]. Given this situation, it is possible to identify the existence of a gap in the science regarding the implementation of dynamic life cycle assessment models in the construction industry, which results in obstacles to mitigating environmental impacts during the operational phase of buildings, which is the longest phase of their life cycle.

As the DLCA method evolves and is implemented, it is possible to think about establishing a possible comprehensive and replicable methodology to transform the static method into a dynamic process that includes a continuous improvement cycle [18]; therefore, a systematic literature search can shed light on identifying the best way forward to improve the dynamic approach to life cycle analyses.

This research aims to explore the opportunities and benefits that DLCA can offer and propose a generalized methodology for conducting these analyses, aiming at the subsequent development of effective strategies that can be adopted in the construction sector and that promote a more sustainable approach to building construction and operation. As a result of the above, the following research questions are formulated to answer them and thus achieve the objectives.

- Assessment Question 1: Considering the evidence in the current literature for the DLCA approach, what are the advantages and potential opportunities, through SWOT analysis, of the DLCA method in the approach to more intelligent, more innovative, and more sustainable buildings? What are the primary technical and methodological errors and challenges encountered when applying DLCA to buildings?
- Response Question 2: What is the current state of science regarding the understanding of DLCA? What is the leading standard for performing dynamic analyses? If dynamic analyses consider temporal and volumetric changes, how do these dynamic aspects vary in each analysis?

By investigating how Dynamic Life Cycle Analysis (LCA) is applied in the construction industry, the current state of this topic in science can be understood theoretically, allowing for an understanding of its strengths and weaknesses. And, in practical terms, it facilitates the creation and implementation of a comprehensive, accurate, and generalizable methodology for any building, promoting the use of LCA as a sustainable analysis tool in the construction industry. By incorporating dynamic data into the life cycle assessment of buildings, a more accurate interpretation of LCA results can be achieved, filling existing gaps in the science and ensuring an efficient and precise evaluation of building operations throughout their life cycle.

This article is divided into four sections. The first is the "Introduction" section, which contains the research context, objectives, hypotheses, research questions, and the novelty of the research. The second is the "Materials and Methods" section, which provides a detailed description of the workflow followed, as well as the materials and instruments used to collect and analyze the data. This methodology provides a solid framework for conducting the research, ensuring the replicability and validity of the results obtained. Next, the "Results and Discussion" section is dedicated to the collection, interpretation, and discussion of the collected data, highlighting patterns, trends, relationships, and contributions identified during the data collection. Finally, the "Conclusions" section presents the main findings of the research clearly and concisely, allowing an understanding of the scientific contribution of this work in the application of the methodology.

2. Materials and Methods

The methodology of this article is based on conducting a systematic literature review to help elucidate the theory of dynamic life cycle analyses. A systematic literature review is a rigorous and comprehensive process of identifying, evaluating, and synthesizing research studies, articles, and other relevant sources of information related to a specific topic [20]. Following a defined protocol, this approach aims to provide a thorough analysis and interpretation of the existing literature to answer research questions, inform decision-making, and ensure that all relevant information is included while minimizing bias [21].

This systematic literature review includes a bibliometric and a bibliographic analysis. To select the articles, we applied the PRISMA protocol, which defined a series of criteria to filter the total number of articles found and focus on a small group of articles of interest [22]. Next, we conducted a SWOT analysis to determine the strengths, weaknesses, opportunities, and challenges presented by the dynamic life cycle approach in buildings, and how this type of analysis can be developed and consolidated.

Several authors have applied different approaches to conducting systematic literature reviews. [23, 24] focused on the need for a good selection of articles and their analysis to obtain meaningful and accurate results. [25-27] went further and found that article selection depends on a good search strategy for what is relevant to the research.

[28, 29] identified that the results can be analyzed to understand different dimensions of the problem, relating them to each other, and identifying that the issue should be approached as a complex that interacts in an interrelated manner. Finally, [30, 31] carried out two studies in which they addressed and explained systematic literature reviews as a schematic and well-structured literature analysis strategy, offering a precise workflow for their replicability.

With these premises in mind, Figure 1 illustrates the fundamental steps of a systematic literature review, organized into three main phases: initial definitions (with objectives, questions, and research strategies), material collection (with selection criteria, data extraction, and evaluation), and analysis of results. The process is represented as a methodological funnel, where the selected literature is refined through bibliometric (quantitative) and bibliographic (qualitative) analyses, resulting in structured results that answer the research questions in a rigorous and well-founded manner. This representation highlights the systematic, transparent, and reproducible nature of the methodology, ensuring the scientific validity of the review.

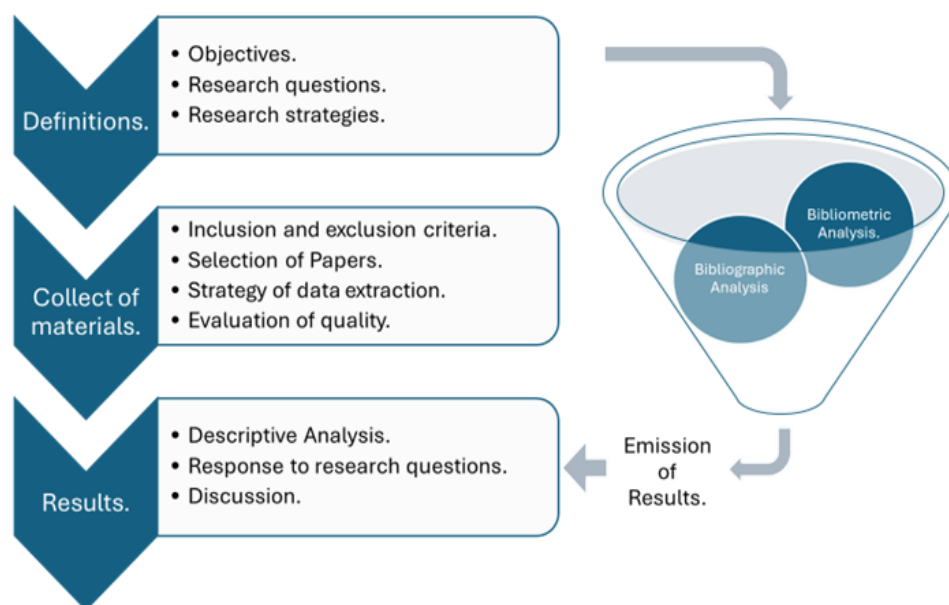


Figure 1 General flowchart followed to conduct this research.

2.1 Research Approach

Specifically, this study adopts a systematic literature review (SLR) methodology to investigate the current landscape and theoretical consolidation of Dynamic Life Cycle Assessment (DLCA) in buildings. The research approach follows a structured protocol based on PRISMA, combining both bibliometric and bibliographic analyses. The objective is to synthesize knowledge, identify research trends, gaps, and challenges, and inform the consolidation of DLCA as a methodological framework (see Figure 2).

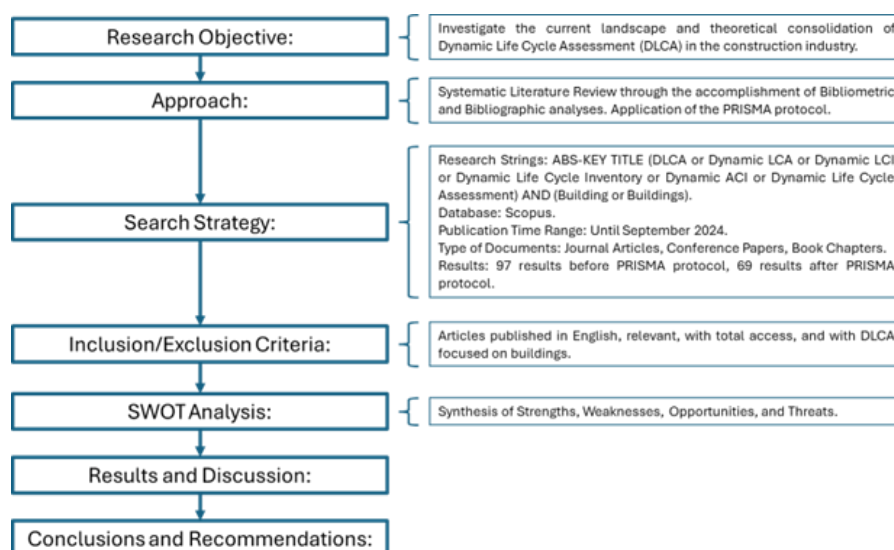


Figure 2 Visualization of the Research Approach.

2.2 Application of the PRISMA Protocol

For the literature search, we initially performed a scope comparison between Scopus, Web of Science, and Google Scholar. This preliminary analysis revealed that the vast majority of relevant

studies indexed in Web of Science and Google Scholar were also covered by Scopus, resulting in substantial overlap. Therefore, we selected Scopus as our sole database because it aggregates a comprehensive and representative set of peer-reviewed journals, many of which are also indexed in other databases, while also offering robust filtering and screening tools suitable for systematic reviews. This choice ensured methodological rigor and reproducibility without compromising the breadth or integrity of the final dataset, as Scopus coverage effectively encompassed the literature relevant to our research scope.

To conduct the systematic review, the objectives, research questions, and strategies were defined. The first two points can be found in the first section of this article. The search strategy was determined by applying the PRISMA protocol, and the Scopus database, widely recognized for its reliability and comprehensiveness, was used to locate the articles [32, 33].

The research topics were entered into the Scopus database, combined with Boolean operators (AND and OR). To further refine the database, only titles, subtitles, abstracts, and keywords were searched. Publications of interest included scientific journal articles, conference papers, and book chapters from various disciplines. The search served to select articles focusing on the use of DLCA in buildings. The keywords were chosen considering that certain combinations can lead to a large volume of articles tangential to the topic.

The other inclusion criteria for the study were as follows: (i) Articles published in English; (ii) Articles published before September 2024; (iii) Articles focused on dynamic life cycle analysis applied to buildings. A total of 97 documents were returned. A summary of these criteria can be seen in Table 1 and Figure 3. This diagram presents the flowchart of the protocol above, used to ensure transparency and reproducibility in the selection of studies included in the systematic review. In addition to representing the basic steps of identification, screening, and inclusion, the diagram reveals essential aspects of the methodological rigor applied. For example, it can be seen that, although 97 records were identified, only 69 were included after a series of justified and documented filters, such as exclusion based on eligibility criteria and failure to retrieve reports. The visualization not only allows us to understand the extent of sample refinement but also demonstrates the use of objective exclusion criteria, demonstrating the robustness of the selection process. The use of PRISMA thus helps to validate the integrity of the review and provide greater reliability to the results obtained.

Table 1 Selection criteria.

Selection criteria	Description
Research Topics	ABS-KEY TITLE ("DLCA" OR "Dynamic LCA" OR "DLCA" OR "Dynamic LCI" OR "Dynamic Life Cycle Inventory" OR "Dynamic ACI" OR "Dynamic Life Cycle Impact Assessment") AND ("building" OR "buildings")
Database	Scopus
Publication time range	Until September 2024
Type of documents	Journal articles, conference papers, and book chapters
Results	97 documents

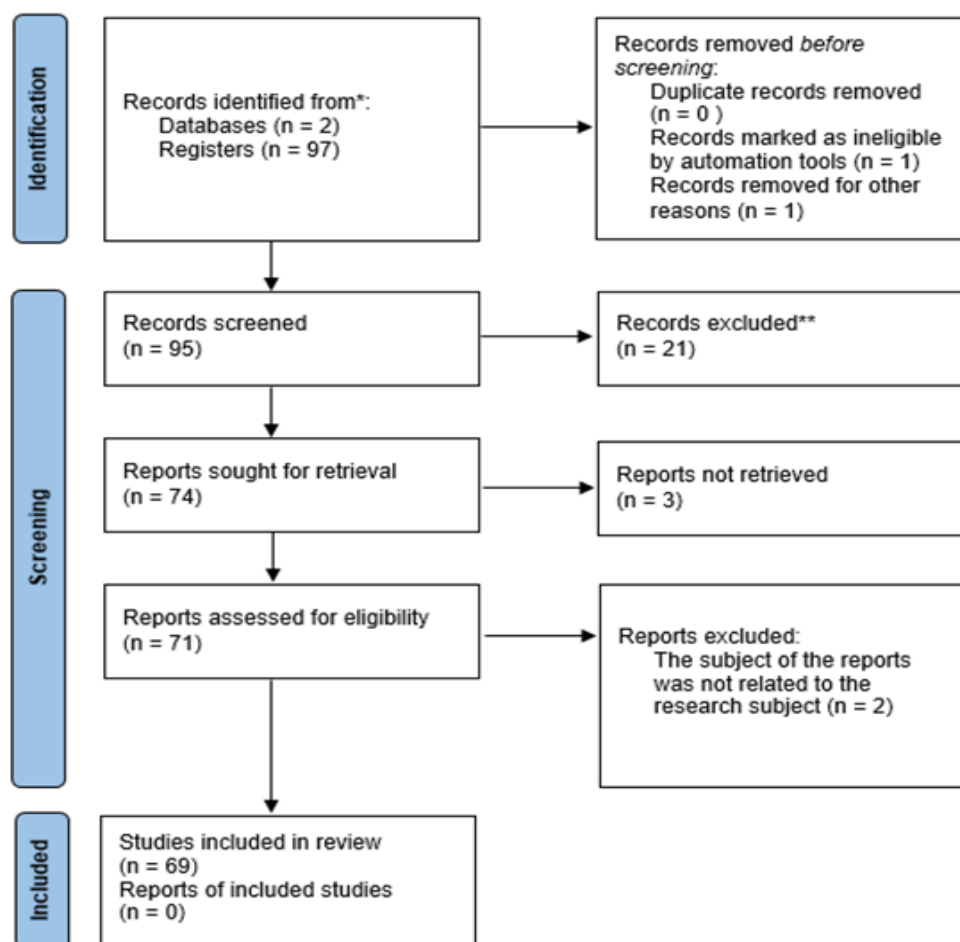


Figure 3 Application of the PRISMA Protocol.

In the preliminary stages of this systematic review, one of our objectives was to understand how the term “Dynamic Life Cycle Assessment (DLA)” and its related concepts have been disseminated in the building science literature. Consequently, we deliberately designed a focused and particular set of search strings to ensure that the retrieved studies addressed DLCA as a core topic, not just superficially. This approach prioritized precision over volume, minimizing the inclusion of articles in which DLCA appears only tangentially in keywords or abstracts; furthermore, the limited dissemination of DLCA-related terminology in the literature, as revealed by this search, is an essential finding of this review, reflecting the current state of DLCA adoption in the field. The complete set of search terms is presented in Table 1, and the implications of this methodological choice are discussed in the results and discussion sections.

The process of applying the PRISMA protocol in this systematic review involved several methodological steps. Initially, 97 references were identified in two databases. After removing duplicate articles (none identified), excluding ineligible articles due to language (one), and excluding irrelevant books (one), 95 articles remained for screening. During screening, these articles were subjected to a qualitative analysis, resulting in the exclusion of 21. Although they mentioned Life Cycle Assessment (LCA), they addressed DLCA (LCA) only superficially, often only in keywords. Of the 74 articles selected, 3 could not be accessed for evaluation and were eliminated. In the final eligibility stage, when analyzing the full content, it was found that 2 articles were not directly related to the topic studied, resulting in 69 studies being included in the review.

Study screening and eligibility assessment were performed independently by two researchers, each working in parallel and unaware of the other's decisions. After the initial selection, any discrepancies were systematically discussed and resolved in collaboration with senior researchers (doctoral fellows and postdoctoral mentors), who are also co-authors of this study. This collaborative, multi-stage process was designed to minimize selection bias and ensure that all included studies met the predefined PRISMA protocol eligibility criteria. Iterative consensus meetings provided an additional layer of verification, increasing the transparency and reliability of the final set of studies included in this review.

2.3 Bibliometric Analysis

In systematic literature reviews, two types of analysis can be considered: bibliographic and bibliometric. Bibliometric analysis identifies publication patterns, research trends, influential authors, and the main thematic areas related to our field of study [34]. It provides a comprehensive map of existing knowledge, enabling us to identify gaps, trends, and places of interest that warrant more detailed and in-depth analysis, thereby focusing attention on the most relevant and significant aspects of the existing body of literature [35].

To perform the bibliometric review analyses, the references included in the search and selection process were exported to Bibliometrix (see Figure 3). Bibliometrix is an open-source program developed in the R programming language for systematically mapping scientific literature [36]. In this research, it was used to obtain a better overview of the selected database, creating clusters of key topics.

Biblioshiny library, derived from Bibliometrix, was used to create a graphical interface for metrics and graphs [37, 38]. This allows visualizing and communicating the results of the literature review more effectively, aiding in the understanding of the patterns, trends, and relationships present in the studied scientific literature [39, 40].

2.4 Bibliographic Analysis

Bibliographic analysis is a process of evaluating and analyzing various sources of information to identify relevant aspects related to a given topic or research object [41, 42]. For this study, a table was constructed to organize the results according to the aspects that comprise dynamic life cycle analyses (See File S1). This table was divided into five columns: authors, article title, applied methodology, and contribution. The articles selected for this analysis were the 69 that remained from the last phase of the PRISMA protocol.

3. Results and Discussion

This section is divided into four parts: the bibliometric analysis, followed by a complementary bibliographic analysis of the previous one, the SWOT analysis, and, finally, the discussion, in which the research questions presented in the introduction are addressed.

3.1 Results of Bibliometric Analysis

The results of this analysis include the number of articles published annually in the DLCA, publications by country, institutions, featured authors, cooperation between governments, a keyword cloud, and the top journals.

3.1.1 Number of Articles Per Year

The number of articles published per year is an important measure to assess the trend of annual production and the relevance of the topic currently, allowing the identification of research gaps and directing efforts to specific areas that may require further research or development [43, 44].

The analyses show results for the period between 2006 and 2024. Of the 97 publications retrieved from the Scopus database, 95 were articles, followed by 24 conference papers and 4 review articles. Editorials, errata, and book chapters collectively represented only one article.

Figure 4 represents the annual distribution of publications selected in the systematic review, between 2011 and 2023. Although the graph shows significant growth from 2017 onward, peaking in 2019, its interpretation goes beyond the number of articles per year. The curve reveals the progressive maturation of the topic over the last decade, with an initial phase of low production (2011–2016), suggesting a field that is still emerging or underexplored. From 2017 onward, an acceleration of scientific output was observed, possibly related to the increased practical relevance of the topic, methodological advances, or changes in research agendas. The peak in 2019 may indicate an inflection point or consolidation of the debate, followed by fluctuations in subsequent years, which may reflect external factors, such as changes in funding policies, thematic redirections, or even the impacts of the COVID-19 pandemic on publication dynamics (in 2020). In subsequent years, production partially recovered, showing growth in 2021 and 2022, but then declined slightly again in 2023, indicating possible fluctuations in continued interest or publishing capacity.

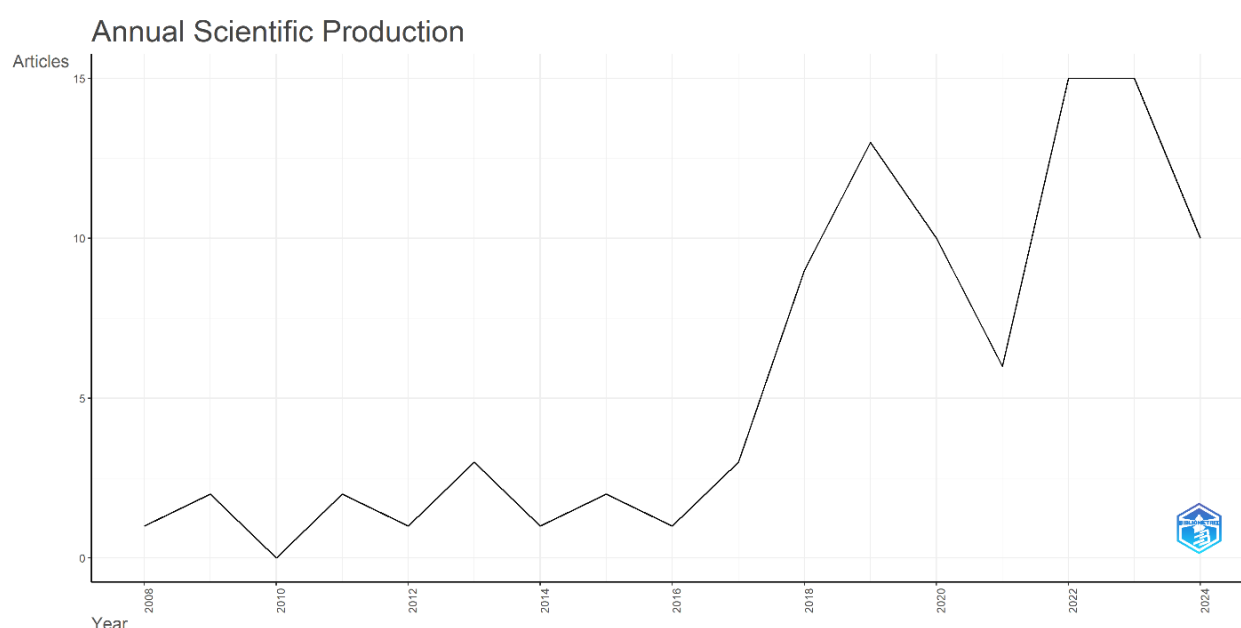


Figure 4 Publications by year.

3.1.2 Publications by Country and Institution

Analyzing publications by country and institution reveals which regions lead in scientific production [44]. This assessment is crucial for promoting international collaboration, diversifying perspectives and resources, identifying disparities in access to or investment in research, and ensuring more equitable and comprehensive representation in advancing the scientific field [43].

Figure 5 presents the geographic distribution of publications on Dynamic Life Cycle Analysis (DLCA), revealing a significant overview of global scientific production. The darker the shade of blue, the greater the number of publications per country, with the United States, China, and France standing out, appearing in the most intense shades. Countries with intermediate shades, such as Germany, the United Kingdom, Australia, and Brazil, also demonstrate significant contributions. Brazil, although represented by a softer color, shows progress on the topic on an international scale, even surpassing some developed countries in the number of publications. On the other hand, large regions in gray, such as most of Africa and Southeast Asia, indicate a lack of or low participation in scientific production on DLCA. This configuration suggests not only a concentration of efforts in established research centers but also raises questions about epistemic inequalities and structural barriers that limit the internationalization of knowledge.

Country Scientific Production

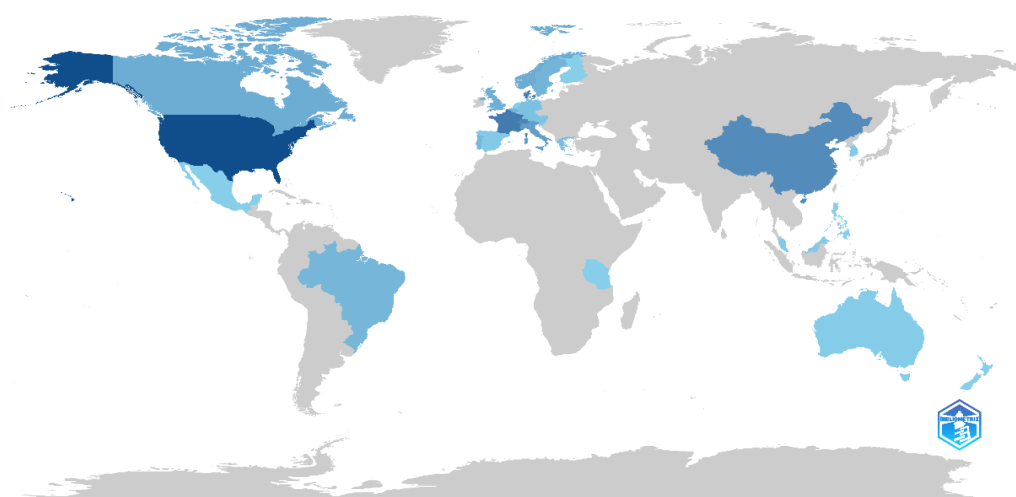


Figure 5 Geographical distribution of DLCA publications.

Figure 6 presents the trend in the number of publications on DLCA by country over time, allowing us to observe distinct patterns of growth and consolidation of international scientific production. China stands out with a steady and significant increase, surpassing 50 publications by 2023, which indicates a coordinated effort to invest in and expand environmental research. The United States, France, and the United Kingdom also demonstrate upward trajectories, albeit to a lesser extent, with the United States maintaining an accumulated leadership position in the field, as evidenced by the overall volume of publications. Countries like Brazil and Canada show more discreet growth, beginning their insertion later and reaching a still modest level, which may be related to structural barriers or different priorities in national research agendas. The figure, therefore, not only reveals the number of studies over time but also allows us to interpret different rates of maturation of the DLCA theme among countries, reflecting their institutional capacities, political contexts, and levels

of engagement with the sustainability agenda. The general trend confirms a global expansion of the field, albeit asymmetrical in terms of speed and volume.

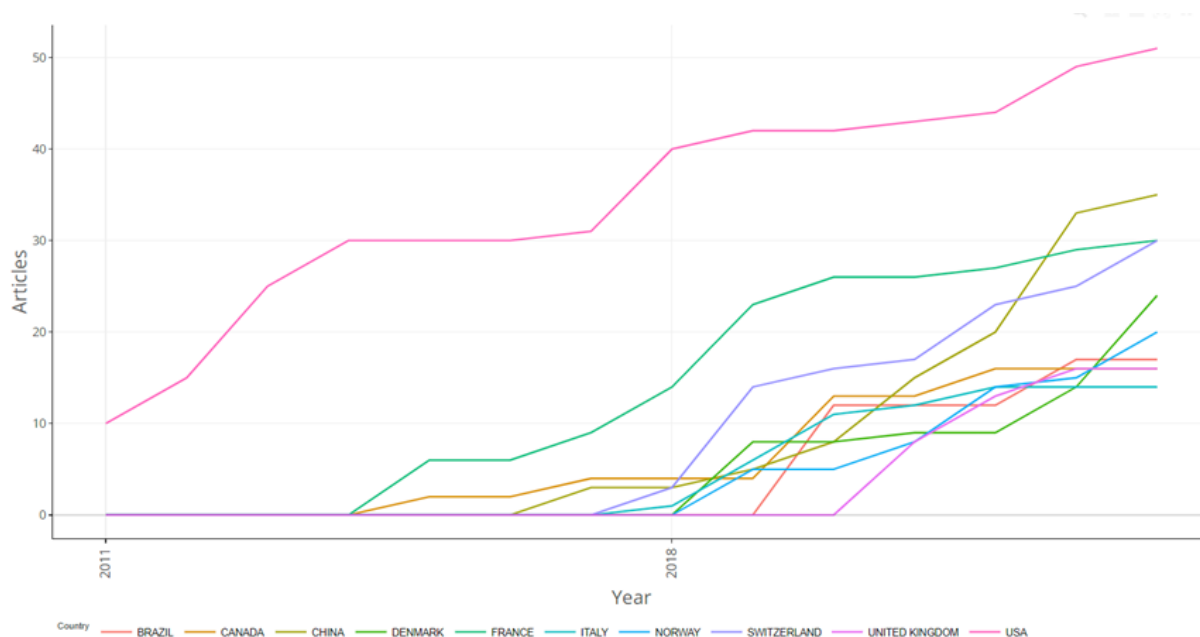


Figure 6 DLCA publication trends by country.

Figure 7 presents the temporal distribution of publications on DLCA by institution, revealing a global and asymmetrical panorama of academic production. The University of Pittsburgh leads in volume, with approximately 30 publications concentrated especially up to 2018, followed by Southeast University and Tsinghua University, both Chinese, which have shown steady and growing trajectories. The notable presence of Chinese institutions highlights China's prominent role in research on sustainability in construction, especially in the context of the DLCA. These institutions not only contribute numerically but also bring valuable perspectives, considering the country's rapid urban development and its growing concern for sustainability.

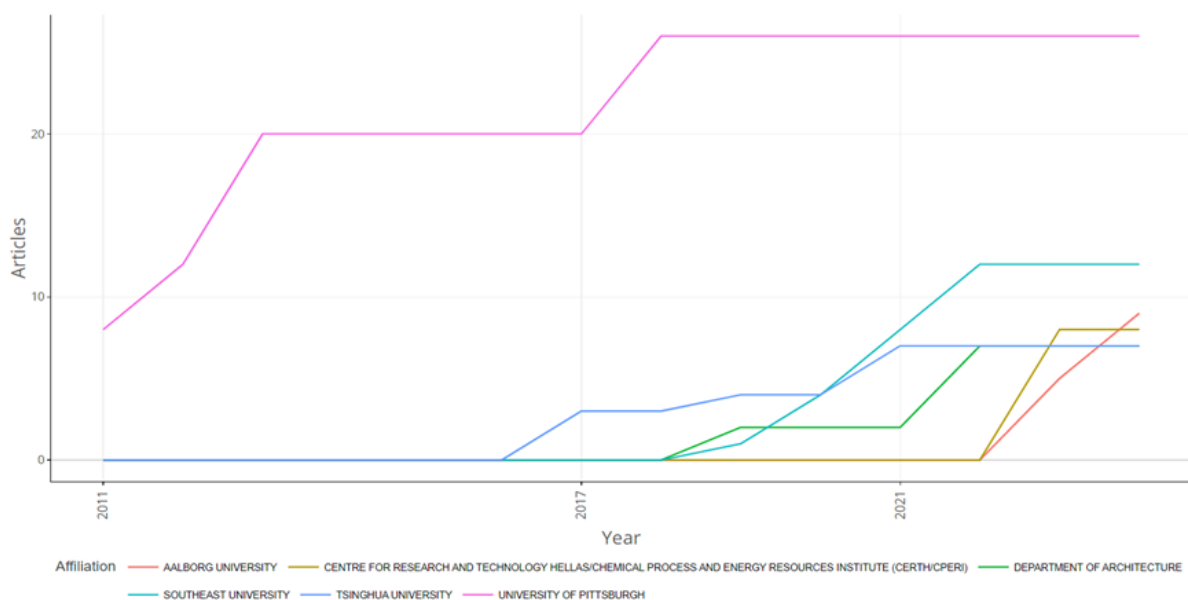


Figure 7 DLCA publications by institution.

On the other hand, European institutions, such as Aalborg University, also demonstrate a substantial commitment, contributing to the diversity of approaches and knowledge on the international stage. Although the University of Pittsburgh stands out for its total number of articles, there was a stagnation in production between 2018 and 2023, which may indicate a shift in institutional focus or line of research. The figure not only highlights which centers produce the most, but also allows us to observe the timing and pace of each group's involvement in the scientific debate, revealing different stages of institutional consolidation. This interpretation helps identify strategic actors, cooperation gaps, and regional research trends, reinforcing the relevance of the DLCA in the field of sustainability and life cycle analysis.

3.1.3 Relevant Authors

Identifying prominent authors allows us to understand who the key researchers are and their contributions to the field [45]. These researchers may represent opinion leaders, pioneers of innovative concepts or methodologies, and catalysts for scientific advances.

Analysis of Figure 8 reveals a dynamic landscape of individual scientific production, highlighting the ongoing contributions of several key authors to the advancement of knowledge. Authors such as Guillaume Harriot, Francesco Pittau, William Collinge, Jay E. Landis, and Alex E. Jones presents a significant and well-distributed output over the years. Harriot and Pittau are particularly noteworthy for their consistent publications, maintaining regularity and impact, reflected in their high citation rates (CT per year). This consistency demonstrates these researchers' commitment to the subject, consolidating their influence within the academic community.

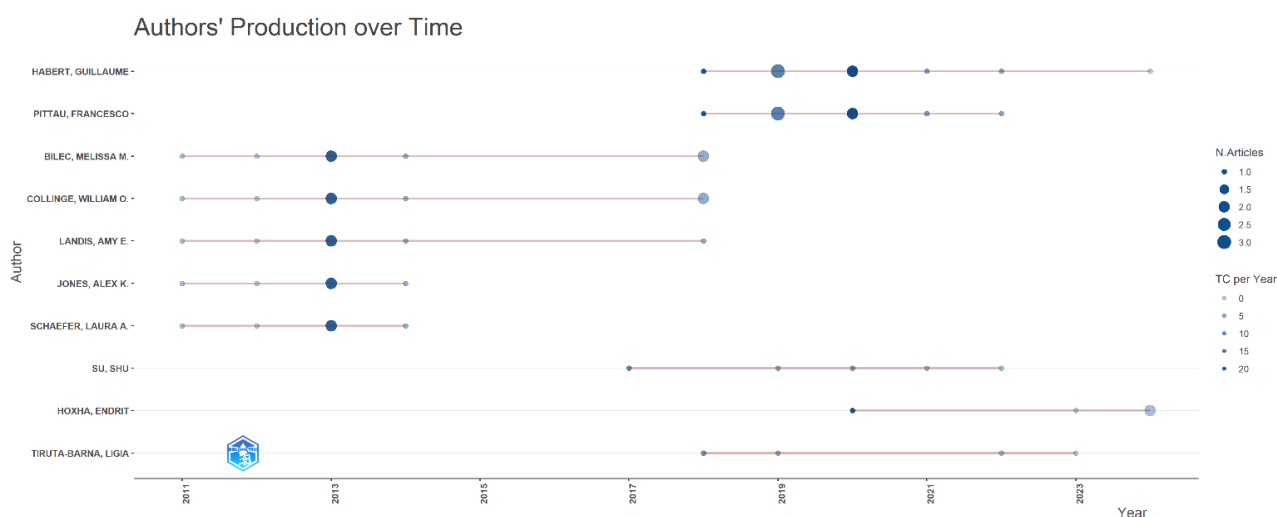


Figure 8 Featured DLCA authors.

On the other hand, authors such as Su Shu and Xiaodong Li, despite presenting a smaller volume of publications, demonstrate notable peaks in impact, suggesting that their specific contributions were highly relevant at certain points. Author Laura Schaefer, on the other hand, presents a production more concentrated in the initial period, but with relatively high impact. It is important to emphasize that the integrated analysis of the number of publications and the impact measured by citations (CT per Year) allows for a broader understanding of academic production [46]. Only by considering these two indicators together is it possible to accurately assess the quality and quantity

of each author's contributions. Consistency over time and recognition through citations are essential factors for understanding each researcher's trajectory and influence on the development of scientific knowledge.

3.1.4 Collaboration Between Countries

Understanding collaboration patterns between countries can reveal established research networks, identify the benefits of cultural and disciplinary diversity in addressing complex problems, promote innovation, and create opportunities to strengthen strategic and interdisciplinary partnerships, as highlighted by [47]. Collaboration between countries reveals how DLCA research is being conducted on a global scale and across multiple fields of knowledge [48].

Figure 9 reveals the geography of international collaboration in research on DLCA in buildings, highlighting the predominance of countries such as the United States, Canada, China, and Western European nations, which appear in darker tones, indicating greater intensity of interactions. The United States, in particular, stands out as a central link, maintaining connections with several global hubs, such as China, the United Kingdom, and Canada. This prominent position may be related to the strong presence of leading institutions in the field, such as the University of Pittsburgh. In contrast, countries with lighter tones, such as Brazil, Australia, and some nations in Latin America and Asia, demonstrate less involvement in transnational collaborations, which may reflect structural barriers, funding limitations, or the absence of robust research internationalization policies.

Country Collaboration Map

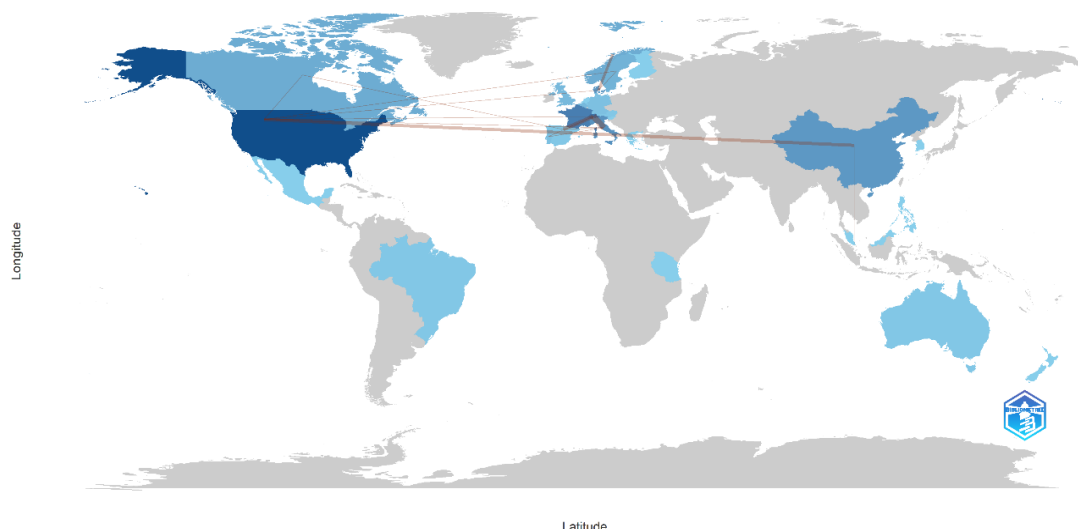


Figure 9 Collaboration between countries in the DLCA.

Promoting international collaboration is essential to the advancement of the DLCA, as it facilitates the exchange of experiences, data, and methodologies tailored to diverse construction and socio-environmental contexts. This exchange contributes not only to the harmonization of standards and databases but also to the development of more robust and representative approaches capable of addressing global challenges, such as climate change, energy efficiency, and reducing environmental impacts in the construction sector.

3.1.5 Keyword Cloud

Understanding keyword clouds is a powerful tool for visualizing and synthesizing the central themes and concepts underlying research, revealing the most relevant topics and connections between different areas of study within the field [49]. Figure 10 shows a cluster of words that appear most frequently in publications. "Life Cycle" is at the center of the cloud, and terms like "life cycle analysis" and "life cycle assessment (LCA)" around the center indicate an approach that departs from traditional (static) life cycle analysis.



Figure 10 DLCA word cloud.

The keywords "environmental impact," "building," "climate change," and "global warming" suggest a particular interest in the climate impacts associated with buildings (see Figure 9). Furthermore, terms such as "greenhouse gases," "carbon," "carbon dioxide," and "gas emissions" indicate a concern with greenhouse gas emissions and the effects of climate change throughout the life cycle of buildings, which could have a broad field of research with a dynamic bias. Energy efficiency and electricity consumption are also areas of focus, as indicated by the terms "energy use," "energy efficiency," and "electricity," when DLCA is applied to assess and optimize energy use in buildings, considering the efficiency of energy systems.

Considering the word cloud, the coexistence of all terms is due to the motivation to apply the concepts together. The absence of some associations may be attributed to the practical impossibility of them or to the lack of initiatives that have explored this approach in depth to date.

3.1.6 Featured Journals

Analysis of top journals (Figure 11) can help identify the most relevant and influential publications in the field, help direct submissions to disseminate findings, and provide insights into quality standards, audience, and research visibility within the scientific community [50].

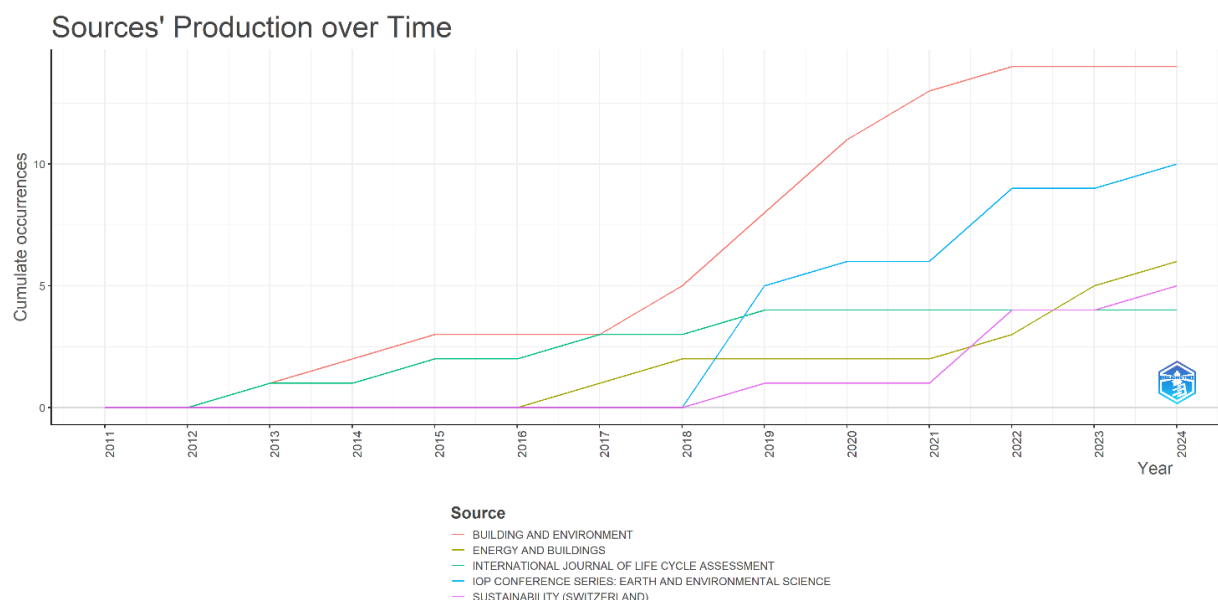


Figure 11 Main journals publishing DLCA.

We identified 30 journals that published articles related to building-related environmental protection (ADL) through 2024. Figure 11 presents the most relevant sources by the number of publications accumulated over time. Building and Environment stands out as the primary source, showing the most significant growth, collecting more than 15 publications by 2024, revealing its considerable impact on the field. Next, Energy and Buildings and Sustainability (Switzerland) show more modest growth, with gradual increases starting in 2017 and 2018, respectively. The IOP Conference Series: Earth and Environmental Science and the International Journal of Life Cycle Assessment also contribute significantly, but to a lesser extent.

A striking asymmetry is observed between the sources, especially when comparing the leading journal with the others. This disparity suggests that each scientific journal prioritizes different approaches, depending on its editorial scope and degree of adherence to the DLCA themes. Journals such as Building and Environment, which focus on sustainability in the built environment, concentrate a larger volume of studies because they are more directly connected to the environmental challenges faced by the sector. In contrast, journals with more general scopes or focused on specific technical niches tend to present more specific contributions. These patterns reveal not only the uneven maturation of DLCA across different scientific communities but also the strategic spaces for its interdisciplinary expansion.

3.2 Results of the Bibliographic Analysis

Considering the 69 articles resulting from the application of the PRISMA protocol, a bibliographic analysis was performed for each of them to understand and document their scientific contributions, thereby determining their progress in the search for a unified and comprehensive method for dynamic life cycle analysis. Furthermore, we focused on the aspects that other authors consider when constructing and applying DLCA. File S1 presents the collected information.

3.3 SWOT Study (Strengths, Weaknesses, Opportunities, and Challenges)

3.3.1 What Are the Advantages and Potential Opportunities of the DLCA Method in Addressing Smarter and More Sustainable Buildings? What Are the Main Technical and Methodological Pitfalls and Challenges in This Regard?

To gain a holistic understanding of the current state of DLCA research, a SWOT analysis was implemented. This organizational strategy summarizes the strengths, weaknesses, opportunities, and challenges identified in the literature review of the various articles studied [51]. The SWOT analysis of the 69 studies can be summarized by observing Figure 12.

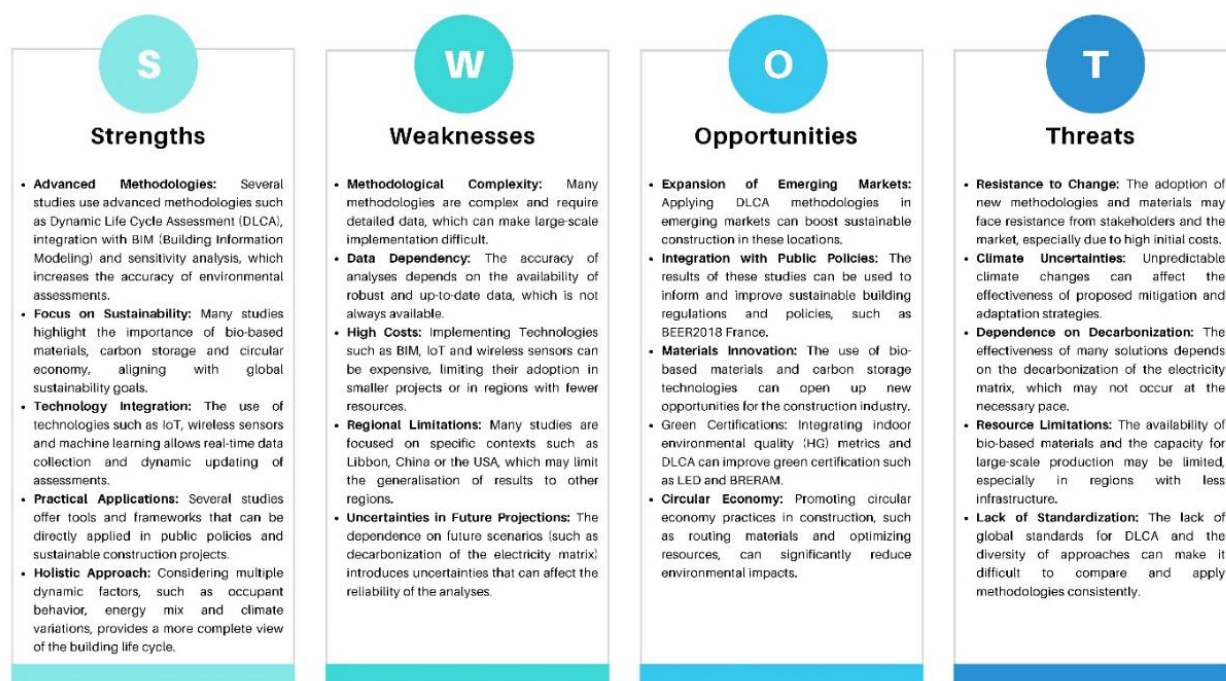


Figure 12 Summary of SWOT analysis.

Among the strengths found are the development of more advanced, simplified, and methodologically integrated methodologies [52-59].

Furthermore, technology integration has been seen as relevant for improving databases through the use of technologies such as IoT, wireless sensors, and machine learning [60, 61]. Several studies explore the connection between DLCA (DLCA) and BIM (Building Information Modeling), which increases the accuracy of environmental assessments by obtaining better quantities of building materials [62-64]. Technology integration has been recognized as a key factor in enhancing databases through the utilization of technologies like IoT, wireless sensors, and machine learning.

There are also studies focused on developing estimates of economic and social impacts [65-67], accurately calculating and reducing environmental impacts [68-74], and developing and meeting climate targets [75-77]. The importance of studying the dynamic impacts linked to the development of bio-based materials [77-79], carbon storage [67, 80, 81], and the circular economy [82] has been highlighted; all in the pursuit of alignment with global sustainability goals.

A necessary strength has been the progress of work that already specifies factors and temporal variables [83-87], integrates or evaluates the impacts of dynamic real data [88-92], and makes short-

and long-term forecasts, as mentioned by [85, 93-95]. These studies considered real-time data collection and dynamic updating of records. The consideration of the dynamic impacts on the development of renewable sources for energy systems, with the improvement of existing networks to guarantee the energy mix, has made significant contributions to the field of DLCA [68, 96, 97].

Among the main weaknesses, the literature consistently highlights the methodological complexity of current DLCA approaches (see Figure 12). These methods are often intricate and hybrid, requiring the integration of multiple models, which complicates their comprehension and application at various scales [53, 58, 62, 67, 89, 97-101]. Additionally, the literature consistently highlights the lack of methodological standardization, including inconsistencies in software tools, database structures, and impact assessment metrics, as a primary barrier to consolidation and broader adoption [55, 73, 79, 102-108].

Another recurring weakness is the dependence on robust, updated, and context-specific data [70, 72, 75, 85, 86, 91]. Several studies report the existence of temporal gaps, where data only cover specific periods, and regional limitations, where datasets are based on geographic contexts such as Lisbon, China, or the USA [74, 92, 102, 103]. These gaps hinder the generalizability of findings and limit the accuracy of long-term projections [52, 56, 75, 84]. Similar constraints arise from the use of region-specific inventories, which create challenges in replicating analyses across diverse contexts [82, 88, 104-106].

Furthermore, they demand detailed, multivariate input data across different scenarios [54], and often rely on extensive flowcharts with numerous sequential steps, increasing the risk of error and limiting reproducibility [57, 63, 69, 93, 100]. Finally, economic barriers also play a crucial role, as the high implementation costs of the necessary technologies and workflows render DLCA less feasible in small-scale projects or regions with fewer resources [59, 60, 66, 68, 96, 107].

However, there are several opportunities that the implementation of the DLCA can seize, such as expansion into emerging markets, as there is a trend towards modernization across global markets, which can boost sustainable construction in various locations. Furthermore, integration with public policies is welcome, as the results of the DLCA can be used to inform government agencies and thus improve or create future regulations [54, 57, 58, 60, 62, 84, 92, 98] and sustainable construction and urbanization policies [88, 100].

Furthermore, innovation in decarbonization materials and technologies can open new opportunities for the construction industry [72, 90, 91, 108, 109]. Similarly, obtaining green certifications for compliance with current environmental regulations and improving sustainability awareness tasks [57, 80] can be considered as other opportunities that exist when implementing DLCA. Integrating indoor ecological quality (IAQ) metrics and DLCA can increase compliance with green certifications such as LEED and BREEAM [47, 52, 63, 66, 71, 110].

Promoting circular economy practices in construction, such as resource optimization, can significantly reduce environmental impacts and other costs in general, making it attractive for implementation in society, specifically for the neediest groups [76]. Furthermore, in the construction sector, other benefits can arise, as it improves the decision-making process of managers [86, 103, 111], renovations are more resilient and sustainable [68, 82, 93, 94, 104], and environmental planning of buildings is improved with better materials and processes [55, 69, 74, 85]. DLCA methodologies can be used to create or reformulate energy efficiency strategies in the built environment and electrical systems, as mentioned by [70, 81, 96, 97, 105, 112].

Several external and internal threats may compromise the broader implementation of DLCA. One significant internal threat is the resistance to change inside the construction industry, where traditional practices are deeply rooted and innovative, especially those involving new materials and methodologies, face skepticism and reluctance [100]; this situation is often aggravated by high initial costs and the lack of proven benefits, as pointed out by [53, 80]. The literature also highlights the ongoing complexity of process models and methods, including highly detailed flowcharts and data-intensive procedures, which may discourage adoption and replication, particularly in resource-constrained environments [52, 59, 60, 72, 90, 92]. In this context, complexity poses a practical threat to mainstream applications.

From an external perspective, uncertainties related to climate change, decarbonization strategies, and global policy implementation timelines pose a substantial challenge to the stability and predictability of DLCA models [67, 104, 110, 111], undermining confidence in the long-term effectiveness of proposed strategies. Additionally, limited access to critical resources such as materials, technologies, and infrastructure threatens the feasibility of DLCA in less-developed regions [68, 110, 111]. The lack of global standards and the diversity of existing approaches make it difficult to compare results across studies and apply DLCA consistently on an international scale [56, 83, 87, 94, 102].

Finally, many DLCA studies neglect behavioral and environmental variables, such as user conduct, occupancy patterns, and climate variation [73, 77, 103, 112, 113]. Combined with the volatility of technological advances and differences in building systems and energy infrastructures [63, 84, 88, 92], these omissions reduce the precision of future impact projections and limit the robustness of the results.

3.4 Discussion

3.4.1 What Is the Current State of Science Regarding DLCA?

Recent developments in DLCA highlight the importance of integrating temporal and regional variability into life cycle assessments to improve the accuracy of environmental impact estimations, particularly in sectors such as electricity generation and construction. Emerging trends include the refinement of temporal modeling, proposals for new metrics regarding Dynamic Global Warming Potential (Dynamic GWP), the correction of previous conceptual limitations, and the implementation of regulatory advancements that set new standards for sustainable buildings (such as France's RE2020, which replaced the RT2012 standard and came into effect on January 1, 2022). Additionally, DLCA has seen the development of more sophisticated methodologies, including hybrid and combined approaches that integrate updated datasets to enhance precision.

There is also a growing emphasis on sustainability in the built environment, particularly through the adoption of bio-based materials in renovations and the tightening of carbon emissions criteria throughout the life cycle of buildings. DLCA applications remain concentrated in residential construction, where key objectives include improving energy efficiency, reducing overall energy demand, and promoting the integration of renewable energy sources. Regarding climate change, DLCA also supports design strategies that ensure indoor comfort during periods of extreme weather, reinforcing its relevance in current building performance discussions.

3.4.2 What Is the Main Standard for Performing Dynamic Analysis?

Dynamic analysis in DLCA commonly involves the use of retrospective time series data to identify trends and forecast future scenarios, while explicitly considering temporal and spatial variability. Current methodologies and new approaches often combine conceptual reviews, mathematical modeling, and dynamic impact assessments to improve analytical precision. Furthermore, these approaches are increasingly aligning with environmental regulations, adapting metrics to ensure compliance with relevant existing and future international standards.

3.4.3 How Do Dynamic Aspects Vary in Each Analysis?

Dynamic aspects in DLCA differ according to the methodological approaches adopted. Some studies utilize retrospective data to assess past impacts and understand the performance; others consider diverse future projections to predict possible environmental outcomes. Methodologies range from conceptual reviews that refine metrics (for example, reformulating the dynamic GWP indicator) to systematic reviews identifying the theory and study trends and challenges, and hybrid models combining both approaches for enhanced accuracy.

As mentioned before, DLCA in the construction sector emphasizes considering new materials for building renovation, which amplifies the scenarios for predictions. Regarding energy in the built environment, studies explore seasonal variations in electricity generation and HVAC system impacts. Climate change-related research is exploring the link between greenhouse gas emissions and global warming, while varying in time.

In general, as can be seen in Figure 13, the application sector of DLCA studies has focused on the construction sector, studying the use of bio-based materials, promoting building renovation, and analyzing environmental regulations such as RE2020. In the energy sector, some research assesses the impact of seasonal variations in electricity generation and the use of HVAC systems. In the case of climate change, several studies focus on the relationship between GHG emissions and the impact on global warming. Another group of studies has compared static and dynamic approaches, showing that the latter provides greater accuracy by including temporal variations in environmental impacts.

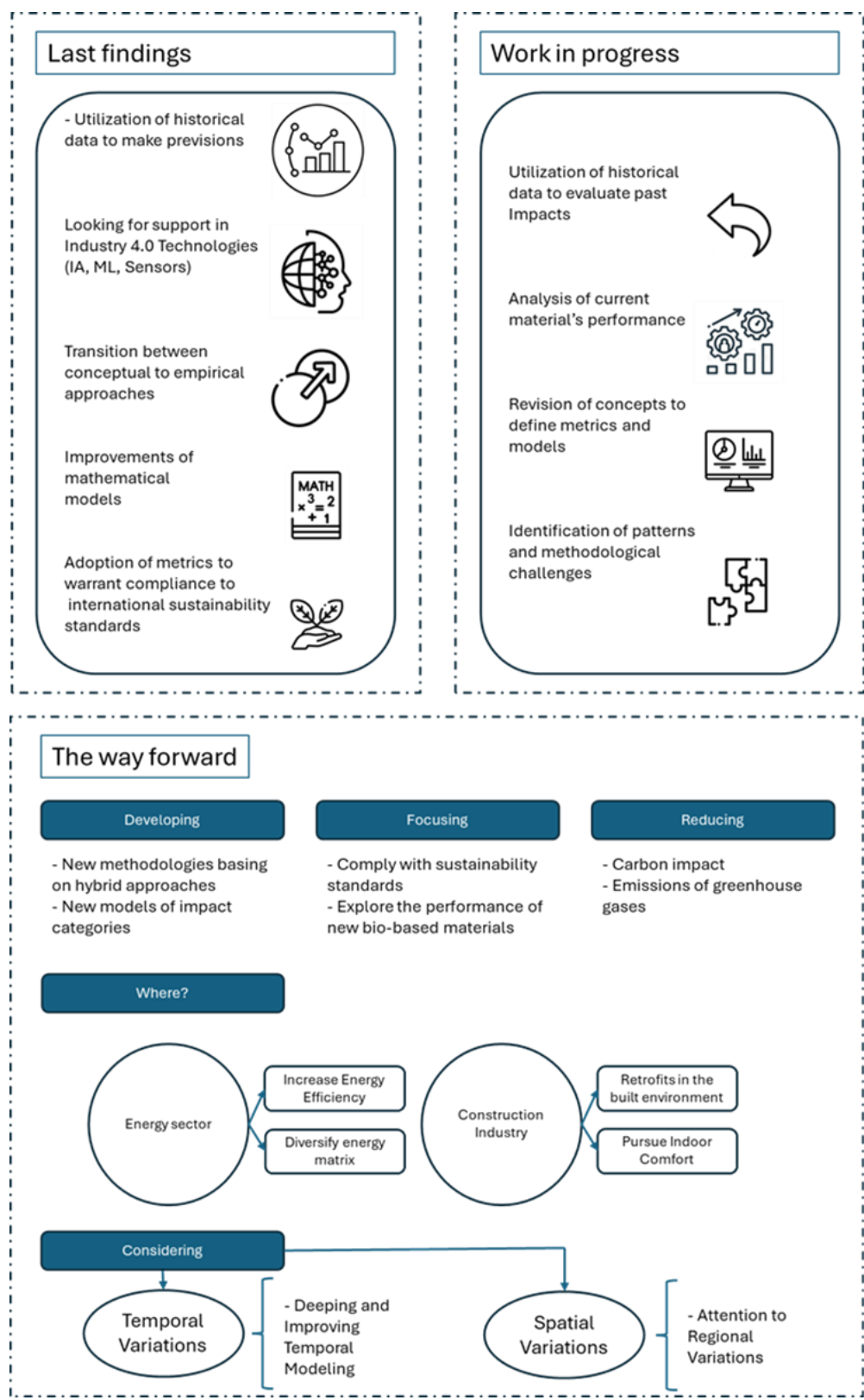


Figure 13 Summary of the state of the art of Dynamic Life Cycle Analysis.

To complement the discussion, a table is presented in File S2. The table in this file presents a detailed structure of the dynamic variables studied in the current literature on Dynamic LCA. It is organized into six main categories: (i) Emissions and Climate Impact, (ii) Energy and Efficiency, (iii) Materials and Resources, (iv) Temporality and Time Horizon, (v) Building Behavior and Use, (vi)

Technology and Innovation, and (vii) Policies and Scenarios. Each category is subdivided into subcategories ranging from global warming metrics to behavioral factors and future projections. The highlighted variables demonstrate the horizon through which Dynamic LCA studies are being structured, highlighting the interdisciplinary nature of the subject, which connects engineering, economics, and environmental science.

An essential contribution of this review is the identification and systematization of dynamic variables that underpin DLCA studies. Table 2 summarizes these variables, organized by category and subcategory, and provides their frequency of occurrence in the reviewed literature, as well as representative studies and their perceived impact on DLCA modeling, as mentioned above. This synthesis highlights the shift from static to dynamic approaches. It underscores the interdisciplinary nature of DLCA, where emissions, energy dynamics, material cycles, temporal factors, user behavior, technological evolution, and regulatory frameworks interact in complex ways. This structured overview allows researchers and practitioners to understand better which variables drive the adoption and methodological development of DLCA in the built environment, supporting future advances in dynamic modeling for sustainability.

Table 2 Summary variables.

Category	Subcategory	Dynamic variable	Frequency	Most Relevant Articles	Impact
Emissions and Climate Impact	Global Warming Metrics	Dynamic GWP (dLCA)	12	Zieger (2020) [52], Ventura (2023) [53], Göswein (2021) [88]	High
		GWI_inst (t)/GWI_cum (t)	9	Fouquet (2015) [58], Su (2021) [62], Pittau (2019) [66]	High
	Carbon storage	Temporary carbon storage	7	Pittau (2019) [67], Carcassi (2022) [68], Peñaloza (2016) [69]	Average
Energy and Efficiency	Energy Matrix	Evolution of the Electrical Matrix	11	Jalaei (2020) [63], Yang (2024) [60], Morales (2023) [98]	High
	Operational Efficiency	Operational Energy Use (B6)	8	Negishi (2018) [91], Collinge (2011) [99], Van de Moortel (2022) [93]	Average
Temporality	Time horizon	Time Horizon (TH)	14	Ventura (2023) [53], Lueddeckens (2020) [83], Zieger (2020) [52]	High
	Dynamic Factors	Dynamic Characterization Factor (DCF)	10	Su (2021) [62], Fouquet (2015) [58], Mosquini (2024) [75]	High
Building behavior	Occupation	Attendance Schedule	6	Negishi (2018) [91], Su (2021) [62], Yang (2024) [60]	Average
	Comfort	Indoor/outdoor temperature	5	Collinge (2013) [89], Su (2020) [10], Morales (2023) [98]	Low
Policies	Regulatory Scenarios	Carbon Budget (2°C)	5	Göswein (2021) [88], Ventura (2023) [53], Mosquini (2024) [75]	Average
		RE2020(t) Factor	3	Ventura (2023) [53]	Average

The table reveals a critical transition in the literature: the swift form of traditional static approaches to dynamic models that incorporate temporal and contextual variables. For example, within the topic of emissions and climate impact, the distinction between static (sLCA) and dynamic (dLCA) GWP highlighted by several authors demonstrates the need to consider the timing of emissions (e.g., CO₂ emitted today has a different impact than CO₂ emitted in 2050). Metrics such as GWI_inst (t) and GWI_cum (t) [58] quantify the instantaneous and cumulative radiative implications, which are essential for evaluating short- and long-term mitigation strategies.

The time factor is essential for the variables that make up a DLCA. Concepts such as time horizon (TH) and dynamic characterization factors (DCF) allow modeling scenarios [83] that can be modified by technological developments and changes in the energy matrix, reflecting the reality of systems in transition.

Furthermore, in buildings, human behavior and the technologies employed are seen as fundamental in some studies to compose the DLCA: variables such as “hours of presence” and “efficiency of photovoltaic systems” [60] show that the environmental performance of a building depends not only on its design, but on the symbiosis of dynamic interactions between users, technology and environment.

3.4.4 What are the remaining gaps and future directions for DLCA?

Figure 13 summarizes the current state of Dynamic Life Cycle Assessment (DLCA), highlighting key advances, persisting gaps, and future research priorities. Recent studies indicate a growing reliance on historical data for forecasting, facilitated by the adoption of Industry 4.0 technologies, including Artificial Intelligence (AI), Machine Learning (ML) models, sensor-based monitoring, and Building Information Modeling (BIM) methodology. There is also a noticeable shift from conceptual frameworks toward empirically based models, each one considering its particularities, accompanied by the refinement of mathematical approaches, and pursuing alignment with international sustainability metrics.

Ongoing efforts focus on consolidating DLCA as a reliable decision-support tool by identifying methodological patterns common to the different studies to overcome persistent analytical challenges. These developments and enhancements are crucial for increasing the practical applicability and replicability of DLCA in real-world building projects.

As illustrated in “The Way Forward” (Figure 13), three strategic research avenues are emphasized: the development of new hybrid methodologies and impact categories to continue exploring scenarios; improved alignment with sustainability standards and performance assessments of different materials; and strategies for reducing carbon impacts and greenhouse gas emissions. Other concrete actions proposed include diversifying the energy matrix, enhancing the efficiency of building systems, and considering the retrofitting of existing infrastructures.

The relevance of incorporating temporal and spatial variability is also underscored, since seasonality, geographic conditions, and regional policies significantly influence DLCA outcomes. This situation requires more sophisticated modeling frameworks that integrate future scenarios, including those that aim to align with global climate goals [53].

The synergy between variables such as temporary carbon storage [76] and recycling rates [54] underscores the potential for incorporating Circular Economy (CE) models into DLCA. Additionally, the integration of DLCA with Building Information Modeling (BIM) indicates a promising

convergence between digital technologies for construction projects and dynamic environmental assessment, improving the potential for data-driven decision-making processes in the construction sector.

Incorporating dynamic variables is critical for addressing the limitations of traditional/static LCA, which overlook temporal changes (for example, material degradation in landfills) and contextual shifts (for example, the decarbonization of the energy matrix), leading to inaccuracies. Variables such as technological evolution [60] and future climate scenarios enable the contemplation of mitigation pathways that could be aligned with international climate goals, such as the Paris Agreement.

DLCA frameworks must increasingly account for nonlinear dynamics and feedback loops, especially in real-world systems involving building occupancy, operational efficiency, and time-dependent emissions. Design-phase decisions, such as material selection, service life, and replacement rates, can significantly shape environmental outcomes [52]. Prioritizing choices with low impact potential is one pathway toward a more resilient and climate-conscious built environment.

As seen in regulations like France's RE2020, dynamic assessments are no longer optional but a prerequisite for regulatory compliance and technological innovation. For this, its integration not only expands the methodological capabilities of LCA but also reinforces its role as a strategic tool for managing the complexities and challenges of the construction industry towards climate change, technological evolution, and human behavior through adaptive and modern models.

Furthermore, understanding dynamic variables is essential to overcome the limitations of traditional LCA, as static methods overlook the temporal evolution of impacts (e.g., material degradation in landfills) and contextual changes (e.g., decarbonization of the energy matrix), resulting in cyclical inaccuracies. In this same scenario, variables such as "grid technological evolution" [60] and "future climate (RCP8.5)" allow for the simulation of mitigation trajectories in line with the Paris Agreement, essential for industries and public policies. The dynamic incorporation of variables into LCA models, such as building occupancy, operational efficiency, and temporal emissions (e.g., VOCs), requires models that capture feedback loops and nonlinear effects typical of real systems. Design decisions in building use/operation regarding material use, their service life, and replacement rates [52] can enable more sustainable choices and changing patterns in LCA modeling, starting with prioritizing materials with long carbon storage (e.g., wood over concrete).

In the current scenario, regulations such as the French RE2020 already require dynamic assessments, making DLCA a mandatory tool for regulatory compliance and innovation. Studies of dynamic variables not only broaden the methodological scope of LCA but also position it as a strategic tool for sustainable transition, capable of integrating the world in the face of climate change, technological innovation, and human behavior into adaptive and prospective models.

4. Conclusions and Recommendations

Currently, life cycle analysis has evolved to consider temporal variations in variables and material quantities throughout the life of buildings, paving the way for the implementation of dynamic life cycle analysis. However, obstacles still exist that compromise the accuracy of results and ease of implementation, and these are addressed through hybrid approaches and attempts to improve the

method. This work aims to fill the gap in the scientific field by deepening the study of this implementation in the construction industry, thereby elucidating how to contribute to achieving better results and mitigating environmental impacts during the operational phase of buildings.

The central hypothesis of this work was proven. The objective was achieved: through a systematic literature review, it was possible to obtain a detailed understanding of the current state of science on the topic, its exploration and implementation trends, which variables and parameters should be considered when conducting dynamic analyses, what needs attention and improvement, and which path to follow to refine further and perfect these analyses. The study of strengths, weaknesses, opportunities, and challenges (SWOT) enabled us to clarify the strengths and areas for improvement that are still being explored, ensuring the future development of a valid, comprehensive, and replicable methodology in any scenario within the construction industry.

Through bibliometric and bibliographic analysis, and after organizing the findings using SWOT analysis, the research questions were answered:

- The strengths and opportunities lie in the use of new technologies to monitor the built environment and pass the information automatically to databases of materials, consumables, and variables linked to the DLCA, in addition to complying with sustainability targets and environmental regulations, and to consider the use of new materials and the application of the circular economy.
- The weaknesses and challenges lie in the high costs of implementation, distrust of stakeholders, lack of training, and the existence of complexities in workflows due to incomplete, inaccurate databases and insufficient software.
- The pattern of dynamic analysis today is hybrid and experimental, with attempts to analyze data that is updated frequently, but in a complex and somewhat insufficient way. These vary depending on each author's approach, showing a general lack of standardization and structure in the DLCA method.

This work makes a practical contribution to science by facilitating the development of effective strategies that can be adopted in the construction industry, promoting a more sustainable approach to the design and operation of buildings. In a theoretical sense, it helps to advance and evolve life cycle analysis, making it possible to understand that environmental impacts do not occur statically, but vary according to how the operation of buildings varies. This results in the hope that if we improve the built environment in the interest of sustainability, the impact will be less significant.

The current dynamic analysis model is hybrid and experimental, with attempts to analyze frequently updated data, but in complex and somewhat inadequate ways. These attempts vary according to each author's approach, demonstrating a general lack of standardization and structure in the DLCA method.

Several limitations were encountered in the creation of this work. Consulting the bibliography in only one database can be restrictive and insufficient. Furthermore, not considering works from 2025 means that potentially more recent contributions related to the topic are ignored. Moreover, the PRISMA protocol was applied by only two authors, without considering more authors to contribute to the application of the selection criteria. Finally, only the SWOT analysis was selected to organize the articles' findings, without considering the use of another tool to complement the strategic organization.

Therefore, future studies should consider two or more bibliographic databases to obtain more articles and conduct a more comprehensive analysis, considering the evaluation of the most recent

articles possible; include more authors to apply the PRISMA protocol in the selection of articles; and use more tools to analyze internal and external factors that positively or negatively affect DLCA studies.

The key novelty of this work lies in the critical consolidation of the fragmented knowledge surrounding DLCA in the construction industry and the development of a structured analysis based on the SWOT analytical framework. It identifies and categorizes the main strengths, weaknesses, opportunities, and threats related to the current implementation of DLCA, enabling a clearer understanding of where the field stands and how it can move forward. This study goes beyond descriptive aggregation by offering a synthesis of essential variables and parameters that should be considered in dynamic analyses, an evaluative lens through which DLCA implementation challenges are interpreted, and a strategic roadmap pointing to specific areas for methodological improvement and practical application.

In doing so, the study supports the development of a more standardized, scalable, and operationally viable DLCA methodology that aligns with real-world building practices, reflecting the commitment to advancing the understanding of environmental impacts over time and directing research toward sustainable and cutting-edge technological solutions.

Acknowledgments

The authors have nothing to recognize.

Author Contributions

Pereira, Geysa C.: Software, Conceptualization, Writing – original draft. De Lima, Gabriel B.C.: Software, Conceptualization, Writing – original draft. González, Jorge: Methodology, Writing - review & editing. Haddad, Assed N.: Conceptualization, Methodology, Review and Funding. All authors read and approved the published version of the manuscript.

Funding

This work was supported by the Coordination for the Improvement of Higher Education Personnel – Brazil – CAPES (Financial Code - 001), National Council for Scientific and Technological Development – CNPq (grant number CNPq 304726/2021-4), and Carlos Chagas Filho Foundation for Research Support of the State of Rio de Janeiro - FAPERJ (grant number: E-26/200.342/2023).

Competing Interests

The authors declare no conflicts of interest.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. File S1: Bibliographic and SWOT Analysis.
2. File S2: Dynamic Variables.

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