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Comprehensive review of LCA studies in Civil Engineering

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Abstract

This review explores the application of Life Cycle Assessment (LCA) within the domain of civil engineering, aiming to provide a comprehensive overview of current research, methodologies, challenges, and future trends. LCA serves as a pivotal tool for assessing the environmental impact of infrastructure projects, yet gaps persist in its integration with socioeconomic dimensions, regional considerations, and dynamic modeling. By analyzing existing literature and scholarly discussions, this review identifies research gaps and proposes directions for enhancing the applicability and effectiveness of LCA in civil engineering. Moreover, it examines future trends such as the integration of advanced technologies, stakeholder engagement, and policy implementation, which are poised to shape the landscape of LCA practices in the civil engineering sector. Ultimately, this review paper contributes to the understanding of LCA's potential to drive sustainable decision-making in infrastructure development, paving the way for more informed and environmentally conscious practices.

Keywords
Life Cycle Assessment, Civil Engineering, Environment, Indicator, Building, Road.

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1 Introduction

The field of civil engineering has witnessed a growing emphasis on sustainable practices, driven by the need to address the environmental impacts of construction and infrastructure projects. In this context, LCA has emerged as a powerful tool for evaluating the comprehensive environmental implications of buildings and infrastructure throughout their entire life cycle. LCA assesses the environmental burdens associated with each phase of a project, from raw material extraction to construction, operation, and end-of-life scenarios. LCA is particularly relevant in the construction sector, which significantly contributes to energy consumption, resource depletion, and greenhouse gas emissions.

1.1 Historical Development

The historical development of the LCA can be divided into distinct periods. The years 1970 to 1990 marked the "Decades of Conception," during which early studies emerged, addressing environmental concerns such as energy efficiency, pollution control, and waste management. The scope of analysis expanded to include resource requirements and waste flows, with pioneering studies on beverage containers conducted by the Midwest Research Institute and Basler Hofman. Interest waned briefly, but by the early 1980s, it surged. The period from 1990 to 2000 saw the "Decade of Standardization," characterized by coordinated efforts through organizations such as SETAC and ISO to create a framework and terminology for LCA. This era also saw the integration of LCA into policy documents and the emergence of impact assessment methods. The following decade, 2000 to 2010, was labeled the "Decade of Elaboration." Diverse LCA methods were explored, ranging from economic and social impacts to dynamic and risk-based assessments. The field has expanded to cover not only environmental aspects but also societal and economic dimensions. The future (2010-2030) was anticipated as the "Decade of Life Cycle Sustainability Analysis," emphasizing a broader approach encompassing environmental, economic, and social indicators and spanning various levels of analysis from product to economy-wide assessments. This phase of development aims to address complex sustainability challenges through an integrated and transdisciplinary framework [1].

1.2 Need of LCA in Civil Engineering

The 2030 Agenda's 17 Sustainable Development Goals (SDGs) were adopted by global leaders in January 2016. Concurrently, the Paris Agreement emerged from COP21 in November 2016, uniting countries to limit global temperature rise below 2 degrees Celsius. By April 2018, 175 parties had ratified the agreement, with 10 developing nations outlining climate change response plans. Climate change disregards borders, as evidenced by rising greenhouse gas emissions impacting weather patterns and sea levels [2]. A distinct SDG targets urgent climate action. Life cycle assessment aids sustainability experts, designers, and engineers in evaluating products and systems alongside alternatives. To ensure unbiased comparability, the International Organization for Standardization (ISO) established global benchmarks, with the European Committee for Standardization (CEN) enhancing assessments for specific domains such as construction materials. A new CEN standard under development focuses on sustainability assessment methodologies for civil engineering projects [3].

This article provides an in-depth overview of the latest developments in Life Cycle Assessment (LCA) within civil engineering. This section covers the tools used for analysis and the databases containing life cycle inventory (LCI) data. The article also includes constructive criticisms addressing both the limitations of LCA and the practical challenges that have arisen. The main objective of this study is to enhance our understanding of how LCA is applied in civil engineering. This, in turn, encourages the use of LCA as a tool for making informed decisions in managing infrastructure projects. Furthermore, this article aims to establish new criteria for designing with the environment in mind.

2 BASIC FRAMEWORK OF THE LCA

Life Cycle Assessment (LCA) is a standardized approach used to systematically analyze the environmental impacts of a product or service from its inception to its functional end. It encompasses stages such as raw material acquisition, production, usage, maintenance, and end-of-life. These impacts include resource depletion, human health, and ecological well-being [4]. Despite its current application in various industries with diverse methodologies, LCA's origins date back to the 1970s. While ISO standards such as 14040 and 14044 provide guidance, they lack practical specifics [5].

2.1 Phases of LCA

Life Cycle Assessment (LCA) consists of four distinct phases. The first phase involves defining the goal and scope of the assessment and setting the boundaries and objectives. In the second phase, the life cycle inventory (LCI) is compiled, where all relevant data on inputs, outputs, and processes within the system boundary are collected. The third phase, known as life cycle impact assessment (LCIA), evaluates the potential environmental impacts of the identified inputs and outputs. Finally, in the fourth phase, the results are interpreted, providing meaningful conclusions and recommendations based on the assessment's goals and findings [6]. The important phases involved in LCA in civil engineering and other important issues are discussed below. Figure 1 below shows the LCA framework.

Goal and Scope

The LCA process begins by defining the goal and scope, which are crucial for selecting methodology and categories. Clear articulation of the study's scope, purpose, and assumptions, including lifecycle phases, future scenarios, and product components is pivotal. This step, which is mandatory in each LCA study, significantly shapes its direction and ensures transparent communication post-study. The scope involves setting the system boundary and level of detail, both influenced by the intended LCA result use and the subject under examination. The scope of LCA varies widely based on its goal, making it essential and variable across cases [7].

Life Cycle Inventory

The Life Cycle Inventory (LCI) involves tracking the inputs and outputs related to a product, requiring extensive regional and global data. The process considers energy and raw materials as inputs, and environmental emissions such as gases, liquids, and solids as outputs. Gathering data for energy, transportation, materials, and waste from sources such as factories, governments, and scientific journals is essential. LCI analysis compiles input/output data within the system boundary, tailored to the study's goal. Specific case data or general databases such as Ecoinvent can be used [8]. Various specialized LCA tools and software are available for conducting LCAs with different levels of detail.

Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) serves to evaluate the life cycle inventory outcomes of an analyzed system. In this process, the various outputs obtained from the Life Cycle Inventory (LCI) are adjusted by a factor based on the unit of measurement. This adjustment assigns the outputs to specific impact categories such as global warming, land use, water use, acidification, and eutrophication. This step is referred to as "characterization." The software provides predefined LCI methods for this purpose. The quantified impact resulting from characterization can then be compared with a reference value, known as "normalization." In addition, quantified impacts can be given significance values, unique to each impact category, for the calculation of a single consolidated outcome. This process is termed "weighting." These significance values are determined on the basis of factors including economic, political, and social considerations [6].

Interpretation

Interpretation in LCA refines and explains the multitude of results to derive meaningful conclusions. Interpretation amalgamates inventory analysis and impact assessment findings coherently with a predetermined goal and scope. This phase unveils potential limitations, drawbacks, and uncertainties [6]. Summarizing and discussing LCI and LCIA results forms the interpretation stage. It leads to conclusions, recommendations, and decision-making aligned with the defined goal and scope. Multi-criteria analysis (MCA) can yield a single weighted outcome, overcoming the need for separate results from each impact category. Employing sensitivity analysis reveals if uncertain inputs significantly influence outcomes, possibly necessitating a more extensive inventory analysis [9].

2.2 Different Life Cycle Models for LCA

To assess a product's life cycle, understanding its stages is essential. The life cycle typically involves five phases: raw material extraction, manufacturing and processing, transportation, usage and retail and waste disposal. Various life cycle models exist, with four common ones: Cradle-to-grave analyzes impact across all five steps, whereas Cradle-to-gate assesses until factory exit. Cradle-to-cradle integrates recycling, closing the loop, whereas Gate-to-gate focuses on specific value-added processes. Environmental Product Declarations (EPDs) certify LCA findings, and there is a specialized Well-to-Wheel approach for transport fuels and vehicles, ensuring precision in emissions and energy calculations [3].

2.3 LCA Tools and Databases

Licensed software tools for LCA, notably GaBi, and SimaPro, utilize databases such as GaBi, Ecoinvent, ELCD, U.S. LCI, IDEA, and Input-Output (I-O) for comprehensive analysis. BEDEC-ITeC focuses on construction with energy, CO2, and pricing data[8]. Comparative reviews of construction-oriented databases highlight Ecoinvent and GaBi as superior, due to qualitative aspects. Ecochain, oneclicklca and openLCA are some other alternative LCA tools. Limited free databases prompt reliance on licensed options, hindering wider LCA application [10]. Accessible databases are essential; their absence restricts LCA studies to experts using licensed software, limiting its broad adoption. Table 1 below shows the advantages and disadvantages of the LCA tools and database.

In summary, LCA tools offer valuable capabilities for assessing the environmental impacts of products and processes. However, their cost, complexity, and dependence on databases can limit their widespread adoption, particularly among smaller organizations and those with limited expertise in LCA methodology. Accessible and current databases are crucial for accurate and meaningful LCA studies. Figure 2 shows the cost optimization process through LCA using different LCA tools and a database.

Table 1: Advantages and Disadvantages of LCA Tools and Databases

Advantages	Disadvantages
1.Comprehensive Analysis	1.Cost
2.Qualitative Aspects	2.Limited Free Database
3.Construction Focus	3.Complexity
4.Alternative Options	4. Database Dependence
	5.Resource Intensive
	6.Data Availability
	7.Subjectivity
	8.Constant Updates

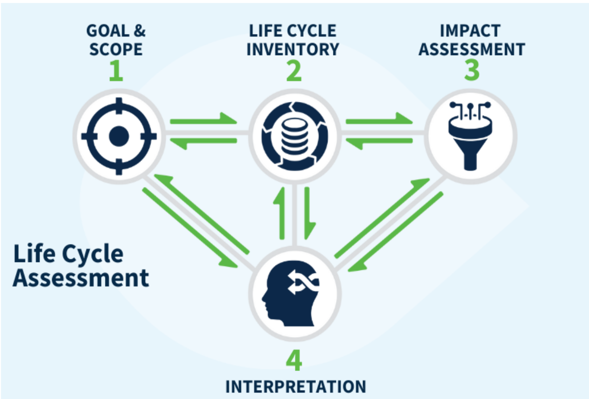

Figure 1: LCA Framework.

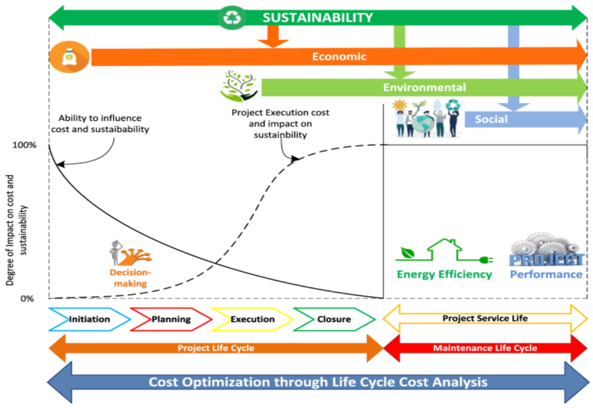

Figure 2: Cost Optimization through Life cycle Cost analysis.

3 Current Practice of LCA in Civil Engineering

In the current practice of Life Cycle Assessment (LCA) in Civil Engineering, the focus is on evaluating the environmental impacts of infrastructure projects from cradle to grave. LCA considers the entire life cycle of a structure, including raw material extraction, construction, operation, maintenance, and eventual demolition or disposal. Advanced software tools and databases are used to model and analyze the various inputs, outputs, and environmental burdens associated with each phase. This aids engineers in making informed decisions to minimize resource consumption, energy use, emissions, and waste generation, ultimately leading to more sustainable and environmentally conscious design and construction practices. In this review, only the structural, geotechnical, highways and construction material domains of civil engineering will be discussed.

3.1 Structural Engineering

In the current practice of Life Cycle Assessment (LCA) in the field of Structural Engineering, the emphasis is on assessing the environmental impacts of building and infrastructure systems. This involves analyzing the complete life cycle of structures, considering factors such as material selection, construction methods, operational energy use, and end-of-life scenarios. Engineers use specialized software and databases to quantify the environmental burdens associated with different structural options.

Majid Bahramian & Kaan Yetilmezsoy conducted a two-decade study on the development of life cycle assessment of the building industry from 1995 to 2018 [11]. The analysis reveals that there was a greater emphasis on studying shorter buildings (1 to 5 floors) compared to taller ones (5 or more floors) in terms of life cycle assessment. Studies on shorter buildings, mainly residential, were about twice as numerous as those on taller buildings, where commercial structures garnered more attention. Most commonly studied were the stages of manufacturing and usage, with a focus on impact factors such as global warming potential and embodied energy. For tall buildings, embodied energy values varied widely from 0.533 MJ/m^2 to 883.1 GJ/m^2, whereas for short buildings, they ranged from 0.21 to 374.4 GJ/m^2. In terms of global warming potential, tall buildings emitted between 10 and 10,010 kg CO_2-eq/m^2 annually, but certain studies highlighted how timber structures could reduce emissions by 234.8 to 1338 kg CO_2-eq/m^2. Emissions for shorter buildings ranged from 0.07 to 35,765 kg CO_2-eq/m^2, with timber structures lowering emissions by 12.9 to 361 kg CO_2-eq/m^2. Lifespan varied widely, from 20 to over 100 years, for different building types in life cycle assessment. Functional units, the measurement units used, also differed substantially, with most using "m^2" (61%), while "whole building" was used in about 20% of studies, showing a lack of standardization. Ecoinvent was the most commonly referenced database (65%) for building life cycle assessment, followed by the University of Bath ICE (11%), the U.S. database (9%), and the Australian material inventory database (7%). Among computer software tools, SimaPro was most frequently cited (40%), followed by ATHENA Impact Estimator (7.5%) and GaBi software (4%). The study underscores that variations in building aspects (design, materials), lifespan, functional units, and scope hinder direct comparisons of research findings [11].

In recent years, major focus areas in building LCA research have been life cycle energy assessment, life cycle carbon emissions assessments, LCA of building refurbishments, dynamic LCA of buildings, uncertainty analysis in LCA of buildings, integration of LCA in building rating systems, integration of LCA with LCC and social LCA and BIM-based life cycle assessment of buildings [12]. A recent study by Fatma Abdelaal and Brian H.W. Guo suggests that using Building Information Modeling (BIM) and Life Cycle Assessment (LCA) for environmentally friendly buildings is not yet fully developed. There is a significant connection between the importance of BIM and LCA for these buildings. The people involved view BIM and LCA positively, seeing their potential for integration. However, the actual use of BIM and LCA does not match these positive views, indicating a need for substantial efforts to effectively implement and integrate them into green buildings [13].

3.2 Highway Engineering

Currently, researchers focus on the field of LCA in Highway Engineering domains, including developing advanced methodologies to quantify environmental impacts, integrating LCA into decision-making processes, and exploring innovative materials and technologies to enhance sustainability in infrastructure projects. Researchers aim to optimize design and construction strategies, minimize energy consumption, emissions, and resource depletion, and promote the adoption of greener transportation solutions to create more resilient and environmentally friendly transportation systems. A study provides a comprehensive review, highlighting research gaps, including areas such as inventory analysis, and locally relevant data collection, addressing aspects such as surface roughness, noise, lighting, and albedo, considering the temporal and consequential aspects of the pavement life cycle and conducting sensitivity analyses [14]. In another study, the use of innovative construction techniques such as 3D printing is being researched [15]. A recent study gathered past research on highway pavement studies, analyzed life cycle steps and environment impact indicators and proposed a method for selecting flexible road pavement structures through stages including design, cost analysis, life cycle impact assessment, and integration of impact assessment with costs. The findings suggest that pavement with a bitumen-stabilized base containing recycled material performs best in terms of cost and environmental impact assessment, given a specific design criterion, while highlighting the influence of design parameters on pavement choices [16]. Another study reviewed various LCA methodologies for pavement and performed a comparative life cycle assessment (LCA) to assess the environmental impacts of using recycled concrete aggregates (RCAs) instead of natural aggregates in Hot Mix Asphalt (HMA) production. The analysis found that mixes with 15% and 30% RCA replacements were more environmentally friendly than the conventional mixture, but the mix with 45% RCA showed poorer environmental performance than the conventional mix [17]. This combined investigation of structure and environment illustrates the benefits of replacing primary natural aggregate (NA) with recycled construction and demolition waste aggregate (CDW-RA) in subbase layers for flexible and semi-rigid road pavements. Various pavement structures featuring a 0.30 m subbase layer constructed from four materials, including two unbound and two cement-stabilized variants using NA and CDW-RA, were compared in terms of their structural behavior. Additionally, the study evaluated environmental impacts through a life cycle assessment (LCA) [18]. Guangli made an LCA framework for bridge assessment[5] and also performed LCA on a soil steel composite bridge [19].

According to [20], 67 LCA studies found in the literature were assessed and categorized into four groups: flexible pavement, rigid pavement, mixed pavement, and road infrastructure. The analysis revealed that 80% of the studies were conducted in developed nations, with only 20% from developing countries. A significant portion of road pavement LCA studies (about 76%) concentrated on material and construction phases, primarily assessing global warming potential and energy demand. A smaller proportion (10-15%) considered a broader range of impact categories and employed commercial software such as GaBi and SimaPro for impact assessment. Of the 67 studies, 19 pertained to flexible pavements, 4 to rigid pavements, 30 to a combination of both, and 14 to road infrastructure. Notably, certain road infrastructure components, such as bridges, tunnels, drainage, lighting, and road marking, were analyzed, whereas others, such as culverts, toll plazas, and vehicle underpasses were excluded. Most studies relied on secondary or background data for life cycle inventory. Only 18 of the 67 studies conducted sensitivity analyses and only 6 performed uncertainty analyses. This study highlights the need to encompass all related infrastructures alongside road pavements and emphasizes a greater focus on sensitivity and uncertainty analyses within transportation sector studies. Therefore, future LCA studies involving road infrastructures should address these negative repercussions and incorporate social and economic impacts via Multi-Criteria Decision Making to enhance LCA as a robust tool for sustainable decision-making [20].

3.3 Geotechnical Engineering

Within the domain of general geotechnical engineering literature, the primary focus of most papers is developmental aspects. These articles also explore approaches to sustainability in geotechnical engineering beyond the realm of LCA and life cycle cost analysis (LCCA). Alternatively, they might involve evaluations of ongoing research endeavors. A study examined sustainability within the realm of geotechnical engineering, emphasizing the importance of resilience and system recovery. They investigated various assessment techniques, including GeoSPeAR, LCA, and LCC. The authors introduced a composite sustainability index that amalgamates resource efficiency, environmental impact derived from LCA, and socioeconomic repercussions during the design process [21]. Another study conducted a comprehensive review of assessments with an environmental focus on the life cycles of geotechnical systems. This exploration identified gaps that could drive future research. While the review's scope was not all-encompassing, it yielded recommendations for future research needs. These suggestions addressed the limited coverage of impact categories in the existing literature and the absence of a standardized LCA framework. The review also acknowledged the impediments posed by the availability and quality of location-specific data, alongside the complexities of evaluating diverse soil profiles and design alternatives [22].

Raymond meticulously analyzed the categories of impact and environmental indicators in the Life Cycle Impact Assessment (LCIA) phase. Specific impact categories, such as energy and global warming, were more frequently used than others. Impacts related to land use and soil received less attention, and the corresponding indicators for these categories were less developed than those related to energy and global warming [23]. In the category of ground improvement, Praticò employed LCCA to develop a model for the selection of stabilizers and stabilization methods for subgrade soil in low-volume road projects. Their method integrated the extra stabilization costs into the construction expenses for treated sections, consequently minimizing long-term maintenance costs [24]. Regarding the category of retaining walls and slope support, Zastrow evaluated 30 cost-optimized earth-retaining walls using LCA, relying on input data from the Ecoinvent database. The quantities of concrete and steel, as well as the recycling status of steel, have implications for the resulting environmental impact [25]. Similarly, Das examined the sustainability and resilience aspects of slope stabilization. Their sustainability evaluation encompassed LCA, socioeconomic consequences, and other factors, each of which was weighted based on their relative significance. Through multicriteria analysis, these weighted indicators yielded resilience and sustainability indices for each stabilization technique. The technique with the lowest index was proposed for implementation. This proposed framework enabled the integration of multiple assessment methods into a single comparable index [26].

In the remaining categories, research was less extensive, and the number of published papers was lower than that other categories. In the category of "Cement related to ground improvement," Chang carried out a comparative study of costs and environmental impacts between the use of biopolymers and traditional Portland cement for ground improvement applications [27].

Table 2: Waste Materials in Concrete Researched in the Past Three Years

Author	Journal	Waste Material Used
R Sharma [28]	Innovative Infrastructure Solutions	Waste coarse aggregate
X Peng et al [29]	Journal of Cleaner Production	Waste coarse aggregate
A Shukla et al [30]	Materials Today: Proceedings	Waste marble dust
Z He et al [31]	Powder Technology	Recycled concrete powder
Z Duan et al [32]	Construction and Building Materials	Waste coarse aggregate and Recycled concrete powder
B Qi et al [33]	Processes	Recycled Epoxy
D Yang et al [34]	Case Studies in Construction Materials	Recycled concrete powder
S Vaishnavi Devi et al [35]	Materials Today: Proceedings	Waste coarse aggregate
D Mostofinejad et al [36]	Journal of Building Engineering	Waste coarse aggregate, recycled fine aggregate, and waste glass
Z Ma et al [37]	Journal of Cleaner Production	Recycled concrete powder
J Xiao et al [38]	Journal of Building Engineering	Recycled concrete powder
Md. Jahidul Islam [39]	Construction and Building Materials	Waste coarse aggregate
Fernando A. N. Silva et al [40]	Buildings	Waste coarse aggregate and recycled fine aggregate
J Kim, H Jang [41]	Journal of Cleaner Production	Recycled concrete powder
Y Guo et al [42]	Construction and Building Materials	Recycled concrete powder
A Aldemir et al [43]	Journal of Building Engineering	Waste coarse aggregate
J. Jolly Abraham et al [44]	Materials Today: Proceedings	Waste coarse aggregate
I Patra et al [45]	Sustainable Energy Technologies and Assessments	Waste coarse aggregate
J Yang et al [46]	Journal of Cleaner Production	Wet-grinded submicron autoclaved aerated concrete waste
K Khan et al [47]	Materials	Waste marble dust
A Zhou et al [48]	Resources, Conservation, and Recycling	Engineering sediment waste
H Al-Mosawe et al [49]	Buildings	Waste coarse aggregate

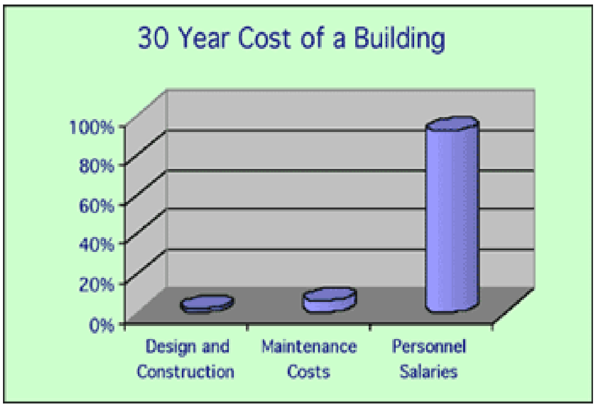

Figure 3: LCA for building construction.

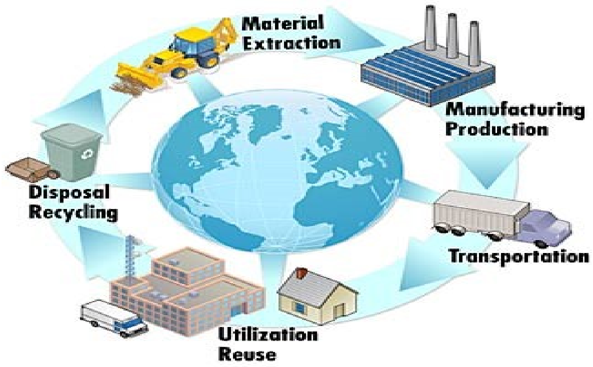

Figure 4: LCA for Geo-technical Engineering Projects.

3.4 Construction Material

Table 2 provides various research that has chosen waste materials, including waste coarse aggregate, waste marble dust, recycled concrete powder, recycled epoxy, waste glass, wet-grinded submicron autoclaved aerated concrete waste, and engineering sediment waste, among others. The diverse range of waste materials explored in these studies reflects a growing interest in finding eco-friendly and cost-effective alternatives to traditional construction materials. These research efforts contribute to the broader goal of reducing environmental impact and promoting sustainability in the construction sector, potentially leading to innovative solutions and practices for the industry's future. To gain a deeper understanding of each study's specific findings and implications, access to individual papers is necessary. Similarly, Figure 4 shows the waste materials used for concrete production over the past three years. The most used waste material was waste coarse aggregate.

Over the past twenty years, research has been directed toward various aspects of the field. For instance, there has been a focus on incorporating Construction and Demolition Waste (CDW) materials as aggregates into new concrete mixtures, as exemplified by references [50].

Furthermore, novel design approaches, including the utilization of building information modeling (BIM), have emerged, as indicated in the references [51]. Additionally, other studies, such as those cited in references [52] have evaluated the environmental advantages of substituting virgin materials with CDW, while minimizing the impact on mechanical properties. Within the construction field, especially in CDW, LCA is commonly employed to select the optimal scenario among landfilling, recycling, and incineration, as discussed in [53]. Research in the past two decades has focused on incorporating Construction and Demolition Waste (CDW) materials in new concrete mixes, exploring design approaches such as building information modeling (BIM) and assessing the environmental benefits of replacing virgin materials with CDW without compromising mechanical properties. These efforts commonly employ Life Cycle Assessment (LCA) to evaluate sustainability impacts across various phases of building and infrastructure projects, but challenges remain in integrating LCA into design considerations and encompassing all lifecycle stages, as highlighted by various literature reviews [54].

Zhuocheng conducted a comprehensive investigation and analysis encompassing 62 peer-reviewed articles, examining aspects such as goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation of the use of timber in mass construction. These studies reveal a broad range of variations in terms of scope, duration, system boundaries, data sources, and indicators. The research covers multiple scales, including building materials, components, structures, entire buildings, and even urban contexts, with a primary focus on comparing the Life Cycle Assessment (LCA) of reinforced concrete (RC) and cross-laminated timber (CLT) constructions. The articles predominantly assess indicators such as global warming potential (GWP) and life cycle energy, indicating that mass timber buildings exhibit, on average, 23.00% higher embodied energy than RC alternatives, while RC buildings demonstrate 42.68% higher embodied greenhouse gas (GHG) emissions than mass timber alternatives [55].

Alireza conducted a systematic review of concrete mixtures and examined the literature concerning the environmental effects related to life cycle assessment (LCA). The analysis encompassed two categories of environmental impact indicators: Midpoint and Endpoint. In the realm of midpoint indicators, various parameters were scrutinized, including global warming potential, water depletion, agricultural land use, fossil depletion, particulate matter, acidification potential, embodied energy, water pollution, ozone layer depletion, eutrophication potential, human toxicity, and abiotic depletion potential. Within the Endpoint indicator category, discussions revolved around human health, ecosystem quality, and resource depletion. It was noted that among the various environmental impact indicators, Global Warming Potential and Acidification Potential were the most frequently employed in the context of LCA for concrete mixtures.

In addition, the author compiled a concise summary of the stages in LCA, taking into account factors such as the country of origin, system boundaries, functional units, effects of service life and compressive strength, sensitivity analysis, and the environmental impact method employed for conducting the LCA. The study revealed that the "crate to gate" approach was the most commonly utilized system boundary in the LCA of concrete mixes, with the CML method being the most frequently employed environmental impact assessment method [55].

4 Limitations and Challenges of LCA in Civil Engineering

In the realm of civil engineering, conducting accurate LCAs encounters numerous challenges. One of the foremost hurdles lies in sourcing precise and comprehensive data, given the multifaceted nature of project life cycles and the inconsistencies in data quality across sources. This is compounded by the scarcity of standardized databases and the resulting uncertainty in assessment conclusions. Moreover, the fast-paced and resource-constrained environment of civil engineering projects often clashes with the time and expertise required for thorough LCA. The industry's deeply ingrained practices and limited awareness about the benefits of LCA can further hinder its integration, while the absence of standardized methodologies prevents cohesive comparisons between studies. The intricacies of civil engineering projects, marked by uncertainty, cumulative effects, and adaptability, make quantifying environmental impacts and setting accurate system boundaries particularly intricate. Implementing Life Cycle Assessment (LCA) in civil engineering projects presents a range of challenges that require careful consideration. Foremost among these challenges is the acquisition of accurate and comprehensive data for all stages of a project's life cycle, a task that can be alleviated through improved data management systems and collaboration with industry organizations. Defining clear system boundaries, fostering interdisciplinary collaboration, and addressing the shortage of LCA expertise are essential to navigating the complexity of LCA. Standardization efforts and adherence to established guidelines can help ensure consistent and reliable results. Additionally, integrating LCA into project planning, educating stakeholders, and advocating for supportive policies can help overcome resistance to change. The dynamic nature of environmental data necessitates sensitivity analysis and scenario planning, while effective communication strategies tailored to different audiences are vital for sharing LCA findings. Overall, these strategies can help civil engineering projects embrace LCA and contribute to more sustainable infrastructure development.

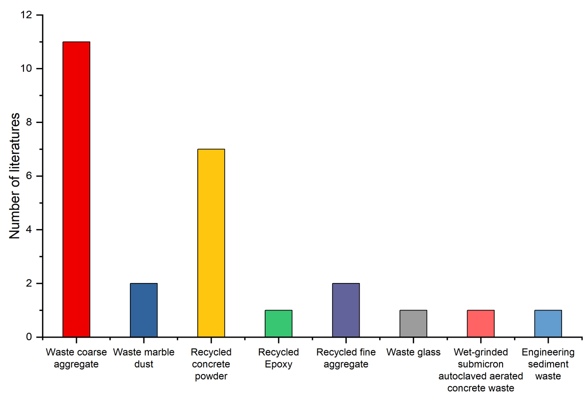

Figure 5: Waste materials used for concrete production in the past three years.

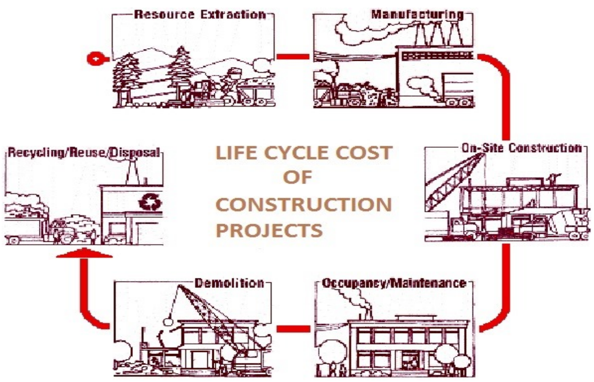

Figure 6: LCA for construction materials in Civil Engineering Projects.

5 Research Gaps and Future Trends

In the context of civil engineering, LCA is a vital tool for evaluating the environmental impacts of infrastructure projects, however, certain research gaps impede its holistic integration. While LCA has primarily addressed environmental aspects, there is a need to incorporate socioeconomic considerations such as community impact and economic development. Existing LCA models are often static, lacking adaptability to dynamic project changes, user behaviors, and external factors. Cultural influences on project outcomes are overlooked, warranting investigation into how cultural factors shape LCA outcomes. Resilience and adaptability also remain underexplored, as is the enhancement of data quality and availability for LCA studies. Moreover, LCA's focus on short-term impacts neglects long-term consequences, necessitating research to incorporate maintenance and adaptation costs. Despite its policy potential, gaps persist in understanding how LCA insights inform policy decisions. Addressing these gaps is poised to drive LCA in civil engineering toward a more comprehensive and impactful future. The future of Life Cycle Assessment (LCA) in civil engineering is expected to involve a holistic approach integrating environmental, social, and economic aspects. This includes evaluating social impacts and long-term economic viability, aided by advanced data analytics, real-time monitoring through digital twin technology, and the application of circular economy principles for waste reduction and material reuse. Collaborative stakeholder engagement, machine learning, and AI are expected to enhance LCA accuracy, while LCA findings could play a more significant role in shaping policies and regulations. Integrating LCA with life cycle cost analysis will provide a comprehensive view of design trade-offs, aligning financial and sustainability objectives for more informed decision-making. Overall, LCA's evolution in civil engineering will be characterized by comprehensive assessments aligned with broader sustainability goals.

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