SUSTAINABLE CONSTRUCTION THROUGH LIFE CYCLE ASSESSMENT: EVALUATING ENVIRONMENTAL IMPACT ACROSS BUILDING STAGES – A REVIEW

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Abstract: The construction sector is one of the world's largest consumers of natural resources and a major contributor to environmental degradation, accounting for nearly 40% of global energy use and around 35–39% of total CO_2 emissions. Sustainable construction aims to reduce these impacts through responsible design, material selection, and energy-efficient practices. Life Cycle Assessment (LCA) has emerged as a powerful tool for quantifying environmental burdens across all stages of a building's life cycle. This review paper examines existing research on sustainable construction and environmental impact assessment using LCA. It presents an overview of a proposed case study on a G+2 Institutional building in Yavatmal, India. The review identifies key impact hotspots such as carbon-intensive materials and energy-demanding phases and highlights the importance of digital tools and integrated management systems in improving sustainability outcomes. The study concludes that LCA is essential for informed decision-making and provides a replicable framework that supports low-carbon construction practices.

Keywords: Sustainable Construction, Life Cycle Assessment (LCA), Environmental Impact, Building Carbon Footprint, Green Materials

I. INTRODUCTION

The construction sector is a major consumer of energy worldwide and a significant source of carbon emissions, contributing substantially to environmental degradation and climate change. A large portion of these impacts arises from the use of energy-intensive materials such as cement, steel, and aluminium, which entail high energy consumption during extraction, processing, and manufacturing. With the ongoing growth in infrastructure development and urban expansion, there is increasing pressure on the industry to adopt sustainable practices that reduce resource use, limit waste generation, and lower greenhouse gas emissions.

Conventional approaches to sustainability assessment in buildings have primarily focused on the operational phase, including energy use for heating, cooling, and electricity. However, such approaches often neglect the environmental impacts associated with earlier and later stages, such as raw material extraction, manufacturing, transportation, construction processes, maintenance, and end-of-life treatment. This limited scope can result in an incomplete understanding of the overall environmental performance of buildings.

To overcome these limitations, Life Cycle Assessment (LCA) provides a comprehensive and systematic methodology for evaluating environmental impacts across all stages of a building's life cycle. It considers the entire process—from resource extraction and material production to construction, operation, and eventual demolition or recycling—thereby offering a complete perspective on environmental burdens. This approach helps identify critical stages or "hotspots" where impacts are most significant and supports more informed decisions related to material selection, building design, construction practices, and end-of-life management.

Within the framework of sustainable construction, LCA has become an important decision-support tool for professionals, including architects, engineers, and policymakers. It enables the assessment of both embodied and operational impacts, encouraging strategies that improve resource efficiency and reduce emissions over the long term. As sustainability standards and certification systems increasingly incorporate life cycle thinking, the role of LCA in promoting environmentally responsible construction practices continues to grow.

This review examines the role of LCA in sustainable construction and outlines the methodology that will be applied in an accompanying case study. By quantifying environmental impacts across all building stages and identifying critical improvement opportunities, this study aims to contribute to a deeper understanding of sustainable building practices and support the development of strategies that advance low-carbon and resource-efficient construction.

OBJECTIVE

The objective of the study is as follows:

1. To understand the basic concept and importance of sustainable construction, along with its role in reducing environmental changes.
2. To apply the Life Cycle Assessment (LCA) method to a building project to evaluate its environmental impact.
3. To study environmental impacts at different stages of the building life cycle, such as material, production, transportation, construction and operation.
4. To identify stages or materials that cause the highest environmental impact (hotspot) using openLCA software.
5. To suggest simple and effective strategies to reduce environmental impacts and improve sustainability in construction.

II. LITERATURE REVIEW

2.1 Introduction

The construction sector has been widely recognised as a major contributor to environmental degradation due to its extensive use of raw materials and energy. According to studies on global construction trends, the industry is responsible for a significant portion of carbon dioxide emissions and resource depletion. Researchers such as Ortiz et al. (2009) and Cabeza et al. (2014) have highlighted the urgent need to adopt sustainable practices to mitigate these impacts.

To address these concerns, Life Cycle Assessment (LCA) has emerged as a comprehensive framework for evaluating environmental impacts across all phases of a building’s life cycle. Standardised under ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b), LCA provides a structured and consistent approach for environmental analysis, enabling better comparison and decision-making.

2.2 Evolution of Life Cycle Assessment

Life Cycle Assessment has evolved significantly over the years into a robust methodology for environmental evaluation. Early work by Guinée (2002) established the conceptual framework of LCA, which was further refined by Rebitzer et al. (2004), who detailed its practical applications and structure. The methodology is typically divided into four main phases: goal and scope definition, life cycle inventory, impact assessment, and interpretation.

Subsequent advancements by Finnveden et al. (2009) and Hauschild et al. (2018) improved the reliability of LCA by addressing issues related to data quality, uncertainty, and impact assessment methods. In recent years, the integration of computational tools has significantly enhanced the applicability of LCA. Software platforms such as OpenLCA (GreenDelta, 2023) and databases like Ecoinvent (Ecoinvent Association, 2023) have enabled more precise and efficient environmental modelling.

2.3 Application of LCA in Buildings

LCA has been extensively applied in the building sector to assess environmental performance across different life cycle stages. Ortiz et al. (2009) demonstrated that material production and operational phases are the primary contributors to environmental impacts in buildings. Similarly, Ramesh et al. (2010) found that operational energy consumption dominates the total life cycle energy use, although embodied energy remains significant during the initial stages.

Cabeza et al. (2014) emphasised the importance of considering both embodied and operational energy to achieve a comprehensive sustainability assessment. Additionally, recent studies such as Pamu et al. (2022) have shown that LCA can effectively compare conventional construction materials with sustainable alternatives, supporting the selection of environmentally efficient options.

2.4 Environmental Impact of Building Materials

The environmental performance of buildings is heavily influenced by the choice of construction materials. Dixit et al. (2012) identified cement, steel, and brick as major contributors to embodied energy due to their energy-intensive manufacturing processes. Similarly, Moncaster and Song (2012) highlighted the variability and complexity involved in calculating embodied carbon in building materials.

To address these challenges, Pomponi and Moncaster (2016) suggested strategies such as optimising material usage and adopting low-carbon alternatives. The use of materials like fly ash bricks and AAC blocks has been explored in studies such as Mahapatra et al. (2017), which demonstrated their potential to reduce environmental impacts while promoting resource efficiency.

2.5 Impact of Construction and Operational Stages

The environmental impacts of buildings are distributed across various life cycle stages, with construction and operation playing critical roles. Sartori and Hestnes (2007) reported that operational energy accounts for the largest share of total life cycle energy consumption in buildings. This finding was further supported by Pérez-Lombard et al. (2008), who analysed global energy use patterns in buildings.

Although the construction phase is shorter in duration, it contributes to emissions through transportation, equipment usage, and on-site activities. Negishi et al. (2018) introduced the concept of dynamic LCA, which incorporates time-dependent variations in environmental impacts, providing a more realistic assessment of building performance.

2.6 Sustainable Construction Practices

Sustainable construction focuses on reducing environmental impacts while ensuring economic and social benefits. Kibert (2016) emphasised the importance of integrating sustainability principles into all stages of construction, including design, material selection, and execution. Similarly, Zuo and Zhao (2014) reviewed global green building research and highlighted the growing importance of sustainable practices.

In the Indian context, frameworks such as the Energy Conservation Building Code (BEE, 2017), GRIHA (2019), and IGBC (2020) have been developed to promote environmentally responsible construction. The adoption of renewable energy systems, efficient building designs, and alternative materials has been shown to significantly reduce environmental impacts and improve long-term performance.

2.7 LCA Tools and Databases

The effectiveness of LCA largely depends on the tools and databases used for analysis. OpenLCA (GreenDelta, 2023) is one of the widely used software platforms due to its flexibility and ability to integrate multiple data sources. Databases such as Ecoinvent (Frischknecht et al., 2005; Ecoinvent Association, 2023) and ELCD provide standardised inventory data for accurate modelling.

Impact assessment methods like ReCiPe 2016 (Goedkoop et al., 2016) enable comprehensive evaluation of environmental impacts across multiple categories. These tools allow researchers to conduct scenario analysis and compare different construction alternatives, thereby supporting informed decision-making in sustainable development.

2.8 Research Gap

Despite the extensive body of research on LCA in construction, several gaps remain. Many studies, including those by Ramesh et al. (2010) and Cabeza et al. (2014), tend to focus on either embodied or operational impacts rather than integrating both within a unified framework.

Additionally, the reliance on generic databases limits the applicability of results to specific regional contexts, particularly in developing countries like India. Mahapatra et al. (2017) emphasised the need for region-specific data to improve the accuracy of environmental assessments.

Recent studies by Waqar et al. (2025) and Lalmi et al. (2025) also point to the lack of integration between LCA and modern data-driven management systems. Therefore, this study aims to address these limitations by conducting a detailed, stage-wise LCA of an institutional building using localised data and advanced tools such as OpenLCA, along with a comparative evaluation of sustainable alternatives.

III. PROPOSED METHODOLOGY

1. **Define the Goal and Scope of Study**

The first step is to clearly define the purpose of this LCA, which is to assess the environmental impacts of the G+2 Institutional building throughout its entire life cycle. The functional unit is set as *1 m² of built-up area for a 50-year lifespan*, and the system boundary covers all stages from raw material extraction to demolition (Cradle-to-Grave).

2. **Collect Required Building Data**

Data related to material quantities, construction activities, energy consumption, and transportation distances are gathered from drawings, BOQ, and standard material specifications. This data forms the basis for modelling the building in OpenLCA.

3. Develop Life Cycle Inventory (LCI)

All collected inputs, such as cement, steel, bricks, sand, aggregates, electricity, and diesel, are converted into measurable units and organised in a structured form. This inventory represents all flows entering and leaving the building system.

4. Model the Building in OpenLCA

The building is modelled in OpenLCA by creating a new product system and entering all material and energy processes. These processes are linked with database values (Ecoinvent or OpenLCA Nexus). Transportation, construction processes, operational energy, and demolition processes are also included to ensure complete life cycle coverage.

5. Select Impact Assessment Method

In OpenLCA, an appropriate environmental impact method is chosen. The primary method used is IPCC 2013 GWP, which calculates carbon emissions (CO_2-eq). Additional methods like ReCiPe may be used to assess other impact categories such as energy demand, water use, and waste generation.

6. Run Life Cycle Impact Assessment (LCIA)

The software calculates the total environmental impacts of the building across all stages. This includes emissions from material production, transportation, construction, operational electricity use, and end-of-life waste handling.

7. Interpret the LCA Results

The results are analysed to identify "hotspots," such as materials or stages with the highest environmental burden. Typically, cement, concrete, steel, and electricity consumption contribute significantly. The aim is to understand which parts of the building life cycle have the greatest environmental impact.

8. Suggest Sustainable Improvements

Based on identified hotspots, recommendations are proposed. These may include alternative materials (e.g., fly ash cement, AAC blocks), energy-efficient building techniques, reduced transportation distances, improved waste management, or adopting renewable energy systems.

IV. PROPOSED CASE STUDY

Title: Life Cycle Assessment of an Institutional Building for Sustainable Construction Evaluation

This study applies the Life Cycle Assessment (LCA) methodology to an institutional building in order to evaluate the environmental impacts associated with different stages of its life cycle, including construction, operation, and end-of-life. The analysis aims to identify stages and components that contribute significantly to environmental burdens and to support informed decision-making for sustainable construction practices.

Case Study Description

The selected case study is a G+2 institutional building located in Yavatmal, Maharashtra, India. The building has been chosen to represent a typical institutional structure, allowing for a practical assessment of environmental performance under real conditions.

Building Specification:

Building Type : Institutional (G+2)

Location : Yavatmal, Maharashtra, India

Built-up Area : 14858.34 m^2

Structural System : Reinforced cement concrete (RCC) frame with brick masonry walls

Functional Unit : 1 m² of built-up area for a 50-year lifespan

The building consists of an RCC framework containing columns, beams, and slabs, along with burnt clay brick walls for partitions and enclosures.

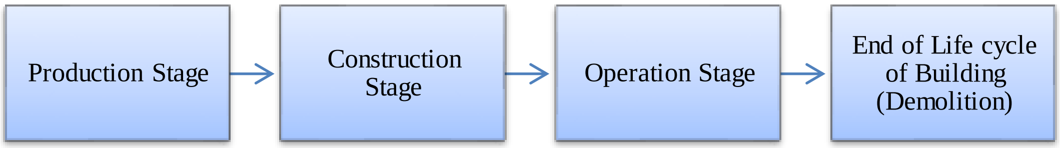

Fig. Stages of building LCA

V. EXPECTED OUTCOMES

The study is expected to develop a detailed environmental impact profile of the selected building by evaluating all stages of its life cycle. This assessment will help in identifying critical stages where environmental impacts are most significant and provide a clear understanding of the overall environmental performance of the building.

The analysis is anticipated to highlight key contributors to environmental impacts, including high-energy materials, construction processes, and operational energy consumption. In addition, the study will perform a comparative evaluation between conventional construction practices and sustainable construction alternatives. This comparison is expected to quantify the differences in environmental performance, demonstrating how the use of eco-friendly materials, energy-efficient systems, and improved construction techniques can reduce overall impacts.

The results are likely to show measurable reductions in key indicators such as embodied carbon, energy consumption, and resource use when sustainable approaches are adopted. Furthermore, the study is expected to identify environmental "hotspots" and provide insights into which stages and components offer the greatest potential for improvement.

Based on these findings, practical recommendations will be developed for enhancing sustainability in building design, material selection, and construction practices. These recommendations may include the adoption of low-impact materials, optimisation of resource utilisation, and integration of energy-efficient technologies.

Finally, the study is expected to establish a structured and replicable LCA-based framework that incorporates both conventional and sustainable scenarios. This framework can serve as a reference for future projects and assist engineers, planners, and decision-makers in selecting environmentally responsible construction strategies.

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CONCLUSION

This review emphasises the increasing significance of sustainable construction practices and the application of Life Cycle Assessment (LCA) in minimising the environmental impacts associated with buildings. The literature clearly indicates that the construction sector is a major contributor to energy consumption, carbon emissions, and resource depletion, highlighting the urgent need to transition toward more sustainable approaches.

The proposed case study demonstrates the practical application of LCA on an institutional building, providing a comprehensive evaluation of environmental impacts across all life cycle stages. By incorporating a comparative analysis between conventional and sustainable construction approaches, the study offers deeper insights into how alternative materials, improved construction techniques, and energy-efficient systems can reduce overall environmental burdens.

The use of tools such as OpenLCA and a life cycle-based perspective enables the identification of critical environmental hotspots related to materials, construction activities, and operational energy use. These insights support the development of effective strategies, including material substitution, optimised design, and enhanced energy performance.

Overall, the findings of this study are expected to assist architects, engineers, and policymakers in making informed decisions that promote low-carbon and resource-efficient construction. Additionally, the study contributes a structured and adaptable framework that can be applied to similar projects, thereby supporting the broader adoption of sustainable building practices.

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