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Carbon Footprint and Life Cycle Assessment in the Built Environment

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Abstract

The building and construction industry contributes to greenhouse gas emissions (GHG) on a global scale and therefore requires effective strategies to minimise the environmental impacts of buildings over their life cycle. This review aims to take a look at the idea of a carbon footprint and Life Cycle Assessment (LCA) and the contribution they make to the promotion of sustainable construction. It explains the main sources of carbon emissions in buildings, such as building embodied carbon, operational carbon, and end-of-life carbon, and the significant carbon contributors. The review provides an overview of the LCA methodology, life cycle stages for buildings and international assessment standards. In addition, it emphasizes carbon reduction strategies involving LCA including low-carbon material selection, circular economy practices, energy-efficient design, renewable energy integration, and BIM (Building Information Modeling)-assisted decision-making. Lastly, current implementation challenges and future directions are highlighted, focusing on digital technologies, built environment whole-life carbon assessment, and policy support for low-carbon and climate-resilient built environments.

Keywords; Carbon Footprint; Life Cycle Assessment (LCA); Built Environment; Whole-Life Carbon Assessment; Sustainable Construction

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1 INTRODUCTION

The building and construction industry is a key driver of economic growth but it is also a major emitter of greenhouse gas emissions (GHG). Whilst energy and carbon intensive materials like cement, steel and concrete are used increasingly to provide infrastructure for growing urban centres, population growth, and rapid urbanisation has led to an increase in their consumption. The sector is responsible for about 37% of world carbon dioxide (CO_2) emissions from energy and process related use and emissions during construction (United Nations Environment Programme (UNEP)), and includes emissions generated during operational activities of the building. This substantial environmental impact has intensified the need to decarbonise the built environment to achieve global climate goals [1], [2].

Energy reduction in buildings is a major focus for sustainable development and towards a net zero carbon emissions. Although the design of buildings for energy efficiency has reduced the operational carbon, there is greater focus on embodied carbon, which is used to describe carbon emissions associated with the use of building materials in their extraction, manufacturing, transportation, building, maintenance and use at the end of their life. Thus, carbon mitigation must take into account the carbon emitted from building over the lifecycle, not just during its use [3].

The carbon footprint is the total amount of greenhouse gas emitted during the life cycle of a product, process or system, measured in carbon dioxide equivalent (CO_2-e). Life Cycle Assessment (LCA) is the internationally standardised methodology (ISO 14040 and ISO 14044) applied to assess environmental impacts of a product or a building throughout the whole life cycle [4]. Whole-life carbon assessment is the integration of both embodied and operational emissions that allows for informed decisions on material selection, design, construction, operation and end-of-life management. This has made it a crucial strategy for creating low-carbon, resource-efficient, and sustainable buildings that contribute to long-term climate change mitigation [5].

2 CARBON FOOTPRINT IN THE BUILT ENVIRONMENT

The built environment is a significant source of global greenhouse gas (GHG) emissions, as buildings consume large amounts of energy and have a long-life cycle, which means they use a lot of resources throughout that life cycle. Emissions occur at all points of material extraction, production, construction, use, maintenance, renovations and demolition [6]. Carbon footprint is an indicator of total GHGs (direct and indirect emissions) arising from a product, process, activity or building expressed in CO_2-e. For the construction industry, carbon footprint assessment offers a holistic assessment of the environmental footprint and helps pinpoint

activities and processes that contribute to high carbon emissions throughout the building life cycle. The information helps in the selection of materials, building design and construction methods, enabling low-carbon development and helping to mitigate climate change and sustainable built environments [7].

Sources of Carbon Emissions in Buildings

i. **Embodied carbon:** Emission generated in the extraction of raw materials, production of building components, transport, construction, maintenance, repair, replacement and renovation during the building's service life, before the building is used.
ii. **Operational carbon:** Pollutants generated from the use of energy in buildings, such as heating, ventilation, air conditioning (HVAC), lighting, hot water and electrical appliances. This is historically the biggest source of building-related emissions.
iii. **End-of-life carbon:** Emission from the end of life of a construction or demolition material, including emissions from its demolition, transportation, recycling, recovery and disposal.

Major Contributors to Building Emissions

i. **Building materials:** They are associated with high energy consumption and high amounts of carbon dioxide emissions in their manufacture, meaning they are high contributors to embodied carbon.
ii. **Construction activities:** Other sources of GHG emissions from construction equipment use, material transport and on-site activities.
iii. **Building operation (HVAC, lighting, and appliances):** During occupancy, continuous energy demand makes a significant contribution to the buildings' operational carbon, especially in low-energy efficient buildings.

3 IMPORTANCE OF CARBON REDUCTION FOR CLIMATE CHANGE MITIGATION

Reducing carbon emissions from the built environment is a key measure to mitigate the climate change and to meet the sustainable development targets globally. The building sector is a major emitter of greenhouse gas (GHG) emissions and reducing the carbon footprint of the built environment can make a significant contribution to limiting global climate change and achieving the goals of the Paris Agreement [8]. Strategies for carbon reduction are in place, such as the adoption of low carbon construction materials, energy efficient building design, renewable energy systems and better construction practices, which will reduce both the embodied and operational emissions [9]. Moreover, whole-life carbon assessment allows stakeholders to

pinpoint the emission hotspots in a building and make decisions based on that understanding over its entire life cycle. Such measures make buildings more energy efficient, conserve natural resources, and increase building resilience, as well as decreasing environmental impacts. Therefore, carbon reduction has a significant influence on the transition towards a low carbon economy in the built environment and sustainable city development [10].

4 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY FOR BUILDINGS

Life Cycle Assessment (LCA) is an internationally accepted and recognised method, standardised by ISO 14040 and ISO 14044, for assessing the environmental effects of buildings over their lifecycle. While most existing methods concentrate on the energy consumption of the operation, LCA considers the impacts of raw material extraction, manufacturing through to construction, operation, maintenance and end-of-life management. LCA quantifies the environmental impacts of energy use, material use, waste generation, and greenhouse gas emissions that become environmental hotspots and allow the comparison of alternative materials and designs. As such it can inform decision making and help foster sustainable, resource-efficient and low carbon building [11], [12].

Four Phases of ISO 14040/14044 LCA

- **Goal and Scope Definition:** Establishes the objective of the assessment, system boundaries, functional unit, assumptions, and intended application of the study.
- **Life Cycle Inventory (LCI):** Involves collecting and quantifying data on material inputs, energy consumption, water use, emissions, and waste generated throughout the building life cycle.
- **Life Cycle Impact Assessment (LCIA):** Converts inventory data into environmental impact categories, such as global warming potential, resource depletion, acidification, and eutrophication.
- **Interpretation:** Evaluates the results, identifies environmental hotspots, assesses data quality and uncertainties, and provides recommendations for improving environmental performance.

Building Life Cycle Stages (Cradle-to-Grave/Cradle-to-Cradle)

- **Raw Material Extraction:** Extraction and processing of natural resources required for construction materials.
- **Manufacturing:** Production of construction materials and building components, including associated energy use and emissions.

- **Construction:** Transportation of materials, on-site assembly, equipment operation, and construction waste generation.
- **Operation and Maintenance:** Energy consumption, repairs, replacement of components, and routine maintenance during the building's service life.
- **Demolition, Recycling, and Disposal:** Building demolition, waste processing, material recovery, recycling, and final disposal at the end of the building life cycle.

Common LCA Standards for Buildings

- **ISO 14040 & ISO 14044:** International standards that define the principles, framework, requirements, and guidelines for conducting Life Cycle Assessment.
- **EN 15978:** European standard for assessing the environmental performance of buildings using a whole-life-cycle approach.
- **EN 15804:** Specifies core rules for developing Environmental Product Declarations (EPDs) for construction products, ensuring consistent environmental data.

5 STRATEGIES FOR REDUCING CARBON FOOTPRINT USING LCA

Life Cycle Assessment (LCA) is an effective decision-support tool which can help identify the carbon intensive stages of a building's life cycle and the strategies to minimise environmental impacts. LCA can be used to evaluate emissions produced during the manufacturing, building, use and end-of-life treatment of materials, and make it possible for stakeholders to consider different design options and apply sustainable methods. The following strategies are well known as methods to lower the carbon footprint of buildings with the added benefits of being resource efficient and environmentally sustainable in the long term [13][14].

- **Selection of Low-Carbon Building Materials:** The options of using materials with lower embodied carbon like recycled steel, low carbon cement, engineered timber, recycled aggregates, and supplementary cementitious materials, have a significant impact on reducing greenhouse gas emissions. LCA can be used to compare environmental impacts of material options throughout their life cycles [15].
- **Material Efficiency and Circular Economy Concepts:** Optimised Structural Design, reuse, recycling of construction waste and the principle of Circular Economy can help to use construction materials efficiently, which helps to minimize the consumption of resources and embodied carbon and maximize the life cycle of the material [16].
- **Energy-Efficient Building Design:** Passive design features, optimized building envelopes, natural ventilation, daylight use, high performance insulation and energy

efficient HVAC systems lower operating energy consumption and carbon emissions during a building's useful life [13].

- **Renewable Energy Integration:** Renewable energy sources like solar PV, solar thermal collectors, geothermal and wind energy reduce reliance on fossil fuels and carbon emissions. LCA can help to analyze how these systems contribute to the environment in the long term [17].
- **Building Information Modelling (BIM) Integrated with LCA:** By combining BIM with LCA, carbon emissions can be assessed in real-time throughout the design phases. This integration helps to quickly compare design alternatives, select materials, and assess their environmental performance leading to informed and data-driven decisions in sustainable construction [17].
- **Design Optimisation During Early Project Stages:** By using LCA at the conceptual and preliminary design phases, architects and engineers can select the most efficient use of the building orientation, structural systems, materials and energy usage prior to construction. The reduction of the whole life carbon emissions and the building's overall sustainability has the highest potential in the early stages of decision-making.

Table 4: Life Cycle Assessment (LCA)-Based Strategies for Reducing Carbon Footprint in Buildings

Strategy	Implementation Approach	Carbon Reduction Benefit
Selection of Low-Carbon Building Materials	Use low-carbon cement, recycled steel, engineered timber, recycled aggregates, and supplementary cementitious materials based on LCA results.	Reduces embodied carbon associated with material production and transportation.
Material Efficiency and Circular Economy	Optimise material use, minimise construction waste, reuse building components, and promote recycling and material recovery.	Conserves natural resources, lowers embodied emissions, and extends material life cycles.
Energy-Efficient Building Design	Adopt passive design, high-performance insulation, natural ventilation, daylight utilisation, and energy-efficient HVAC systems.	Decreases operational energy demand and associated greenhouse gas emissions throughout the building's service life.

Renewable Energy Integration	Install solar photovoltaic panels, solar thermal systems, geothermal heat pumps, and other renewable energy technologies.	Reduces dependence on fossil fuels and lowers operational carbon emissions.
Building Information Modelling (BIM) Integrated with LCA	Integrate BIM with LCA tools to evaluate environmental impacts and compare design alternatives during project planning.	Supports data-driven decisions that minimise whole-life carbon emissions.
Design Optimisation During Early Project Stages	Evaluate building orientation, structural systems, material selection, and energy performance using LCA during conceptual design.	Maximises opportunities for carbon reduction before construction begins, resulting in lower whole-life environmental impacts.

6 CHALLENGES AND FUTURE DIRECTIONS

Using Life Cycle Assessment (LCA) has greatly enhanced the assessment of environmental impacts in the built environment. It is being implemented in a few countries, but there are still a number of technical, methodological and practical issues that prevent it from taking off. Meanwhile, the progress in digital technologies, data analytics and sustainable construction techniques is opening new possibilities to improve the accuracy and effectiveness of the whole-life carbon assessment.

7 CHALLENGES

However, there are some obstacles to the implementation of LCA in the building sector. The main constraint is the availability and quality of life cycle inventory data; this can easily result in less confidence in the assessment results if the information is incomplete or outdated. Furthermore, due to the differences in the databases, system boundaries, and methodological assumptions used by various LCAs, the results obtained from different LCAs can vary, which makes it difficult to compare different studies. Variations in emission factors within a region due to different energy mixes, transportation systems and construction methods also impact the accuracy of the carbon calculations. The complete life cycle carbon assessment is also complicated by the need to gather a lot of data over several life cycle phases, which brings up technical and computational challenges. In addition, the implementation of LCA is not

widespread in many developing countries because of a lack of expertise, standardised databases, and also because of financial and policy issues [18].

8 FUTURE DIRECTIONS

There is potential for future development to make the building carbon assessment more efficient and reliable. AI-powered digital LCA platforms can streamline data handling and enhance prediction precision, and, when combined with Building Information Modelling (BIM), LCA can offer real-time environmental assessment throughout the design process. New digital twin technologies provide for continuous monitoring of operational carbon during the building's life cycle. Additionally, there will be a reduction in embodied carbon thanks to the increased use of circular construction methods such as material reuse and recycling. The transition to sustainable and low carbon buildings will be increasingly strengthened by the government's regulations and policies that require whole life carbon assessments, as well as increasing focus on both net zero and carbon neutral buildings [19].

9 LITERATURE REVIEW

(Ascione et al., 2026) [20] provides an organised evaluation of the literature on the use of life cycle assessment in the industrial building sector, which is still relatively under-represented when compared to residential settings. While the categorisation system was used to a broader sample, including simulated and hybrid scenarios (>230 papers), a thorough and quantitative analysis was carried out for research addressing life cycle assessment (LCA) on existing industrial buildings (20 articles). The review shows that cradle-to-gate techniques are more common, cradle-to-cradle models are employed less frequently, and there are few LCA studies that concentrate on industrial buildings. Health aspects are still under-represented in inventory data collecting, which is still somewhat fragmented and mostly focuses on economic and environmental factors. In order to encourage more uniform, multifaceted, and sector-specific LCA techniques for industrial sustainability planning, the study highlights seven significant methodological shortcomings and suggests a comparison framework that might assist future research.

(Gu et al., 2026) [21] Integrated strategies across the whole lifecycle are needed to manage carbon emissions from buildings. From emission source views to life cycle frameworks based on ISO 21930, which breaks down a building's life cycle into standardised stages, key concepts have changed. The B1-B7 stage and the A1-A5 stage have been the major subjects of previous study, whereas the C1-D stage has received less attention. Traditional estimating approaches, data-driven prediction models (statistical, shallow machine learning, deep learning, and hybrid), and newly developed massive language models are all included in our study of quantification

techniques. Our analysis finds sizable regional variations in policy frameworks: American strategies concentrate on economic incentives, Chinese approaches center on legal regulations, while European frameworks emphasise systematic norms. The United States (12%), Europe (14%), and China (29%) account for the majority of research contributions. We also suggest several reduction strategies from a life cycle viewpoint based on the review.

(C. Li et al., 2025) [8] Calculate the carbon cost of building the world's built environment during the previous three decades and estimate it until 2050. According to research, the carbon footprint of building has quadrupled globally over the last thirty years and is expected to more than double by 2050. Cementitious materials, bricks, and metals accounted for more than half of the construction industry's carbon emissions in 2022. Glass, plastics, chemicals, and bio-based products contributed 6%, while transportation, services, machinery, and on-site activities accounted for the remaining 37%. In the next 20 years, the carbon footprint from building alone will surpass the annual carbon budget for the 1.5 °C and 2 °C targets under the current business-as-usual scenario. According to our research, it will exhaust all of the remaining carbon budget for the 1.5 °C objective by 2050. In order to take advantage of economies of scale and pave the way for a revolutionary and sustainable future in building, we support a material revolution, such as replacing traditional materials with bio-based ones.

(TAÇ & EMEKÇİ, 2025) [22] To reduce these negative effects and guarantee sustainable growth, environmentally friendly building techniques must be used. Life Cycle Assessment (LCA) is a method for evaluating how products and services affect the environment throughout the course of their lives, from the extraction of raw materials to disposal. This process involves the production of trash, carbon emissions, resource utilisation, and energy use. Energy consumption and carbon emissions from material production, transportation, construction, operation, and end-of-life disposal are all included in LCA's assessment of a building's environmental effect. The present understanding of LCA in the building industry is compiled and synthesised in this overview of the literature. It discusses several LCA methodological techniques, the types of environmental consequences taken into account, and the advantages and disadvantages of earlier research. Gaining a better grasp of life cycle analysis's place in the construction sector is the goal of this paper. In addition to informing future research, environmentally friendly design, construction, and policy-making, it provides recommendations for advancing sustainable building practices. Future strategies for creating a more sustainable environment will be guided by these factors.

(Seyedabadi & Eicker, 2023) [23] Determine if the present studies have sufficiently filled the knowledge gap by successfully adopting Life Cycle Assessment (LCA) approaches over the whole lifecycle of buildings while providing a suitable level of detail and reliability in their

findings. In the end, the results of this research project will pinpoint the weaknesses and gaps in the existing corpus of knowledge, making it easier to create a roadmap for further study in this area. Important conclusions are shown by this study field's gap analysis. First off, just 9% of earlier study has looked at the whole urban scale, indicating a sizable research vacuum that has to be filled in further studies. Second, a lot of research uses a bottom-up method, which creates a lot of uncertainty and calls for better modelling and uncertainty analysis. Thirdly, although thorough, the building-by-building strategy is expensive and time-consuming, necessitating study on improving its effectiveness.

(Chukka et al., 2022) [24] India's carbon emissions have increased significantly during the past few decades. One of the main causes of global warming is the growth of greenhouse gases to an unimaginable amount. One of the major cosmopolitan cities in India, Chennai contributes more carbon to the atmosphere and GDP. Chennai's infrastructure industry is constantly expanding, necessitating a greater supply of building supplies. The city's urban and suburban areas, where the automotive division, I.T. division, and industrial estates are located, are expanded as a result of the construction of new buildings. Therefore, the carbon emissions of a conventional-material residential building in and around Chennai are the focus of this study. Thus, it is possible to calculate the carbon emissions from traditional buildings, which contribute to climate change and global warming.

(Budajová, 2021) [25] The term "carbon footprint" refers to the emissions of gases utilised by people that have an impact on Earth's climate. The environment is significantly impacted by construction, building materials, structures, or the entire life cycle of a building. With a lower carbon footprint, sustainable architecture is becoming more and more popular. Sustainable building, which is always evolving, is becoming more and more popular in today's construction sector. We are being forced to cut back on our greenhouse gas emissions due to the extreme weather variations that occur every day. We may calculate a product's carbon footprint by using the global warming potential (GWP) that results from these greenhouse gas emissions, which is raised to carbon dioxide CO2 and represented as carbon dioxide equivalent CO2eq. The purpose of this article is to use life cycle assessment (LCA) analysis to vary the three compositions of the perimeter walls and select the composition that has the lowest carbon footprint, making it more favourable. Because of its beneficial effects on the environment, a sustainable built environment is desperately needed.

10 CONCLUSION

Reducing carbon is essential to sustainable development and the built environment is one of the biggest contributors to global GHG emissions. This review shows that Life Cycle Assessment

(LCA) is a holistic tool to analyse the environmental effects of a building from the raw material extraction to its dismantling and material recycling. LCA can pinpoint emission hotspots to help make informed decisions in material selection, construction techniques, energy use and renewable energy integration. The review also identifies the key role to be played by the use of low carbon materials, circular economy concepts, BIM-integrated assessment and early design optimisation in reducing embodied carbon emission and operational carbon emissions. While there were some issues covered, such as data quality, methodological differences, regional differences, and limited use of AI tools in developing countries, the future is bright as AI, digital twins, digital BIM–LCA platforms will increase the accuracy of assessment and decision making. The global sustainability and decarbonisation agenda will be further reinforced by strengthened policies and mandatory whole-life carbon assessment, which will help speed up the transition to resource-efficient, net zero and climate-resilient buildings.

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