Life Cycle Assessment of Embodied Carbon in Buildings

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The environment demands a reduction in greenhouse gas (GHG) emissions, as building and construction are responsible for more than 40% of the energy consumed worldwide and 30% of the world's GHG emissions. Many countries have aligned themselves with the Paris agreement, following its target of achieving net zero carbon emissions, although some governments are focused on the operational energy efficiency part of the equation instead of the whole equation. Building embodied carbon assessments can be compared to the more widely used and standardized life cycle assessment approach in terms of methodology (LCA), which focuses on quantifying carbon emissions throughout a building's life cycle.

Keywords: life cycle assessment ; net zero ; carbon emissions ; embodied emissions ; uncertainty analysis ; lifecycle stages

1. Introduction

The major source of carbon emission is continued to be buildings and construction, accounting for 40% of all emissions connected to energy. Of the 40%, 12% comes from embodied carbon (EC), which is associated with different stages over the life cycle of the building. The remaining 28% represents the carbon offset, which represents different energy usages in building operations such as heating, cooling, and electrical appliances [1][2]. According to research, with the surge in urban sprawl, GHG emissions may be doubled in relation to the construction and building industry in the following 20 years if significant improvements in building efficiency are not made [3]. The different stages of a building's life over which the emission of carbon and energy use occur are: (I) material extraction, (II) material processing and component manufacturing, (III) construction and assembly, (IV) operation and service, and (V) end of life (EOL); these stages cover the assessment of the building from cradle to grave [4]. In addition, the transition between these phases accounts for considerable emissions related to transport, which is a consequential aspect, that must be considered in carbon emission estimation.

Embodied carbon generally refers to the carbon dioxide (CO_2) emissions associated with the construction and material life throughout a building or infrastructure's whole life span. It includes any CO_2 produced during the extraction, transportation, and fabrication of building materials, as well as the transportation of those items to the project site and the construction methods utilized. Simply put, embedded carbon refers to a building's or infrastructure project's carbon footprint before its completion. It also refers to the CO_2 emitted when maintaining and eventually deconstructing the structure, as well as transporting and recycling the garbage. Carbon that is produced through electricity, heat, lighting, and other sources is not the same as carbon that is embodied.

Building embodied carbon assessments can be compared to the more widely used and standardized life cycle assessment approach in terms of methodology (LCA), which focuses on quantifying carbon emissions throughout a building's life cycle. Single-point estimations of an average numerical output based on deterministic data typically lack the relevance or variability of that number. In comparative studies, the LCA point value findings are superposed and directly compared, for example, when the performance of two buildings is evaluated. The ostensibly less harmful option is chosen without regard for the possibility of making a mistake.

2. Estimation of the Embodied Carbon of Buildings

Currently, life cycle assessment (LCA) is considered the most practiced methodology used to evaluate environmental issues in the context of buildings [5]. It offers a framework for measuring and evaluating environmental effects over the whole life cycle of a system of goods or services, from conception to disposal [6]. It streamlines the estimating approach, and is thus commonly used in evaluating a building's energy and carbon footprint. The International Organization for Standardization has formalized four major steps of the LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO-14040, 2006) [6]. The objective of the system, as well as the system's boundaries and functional units, must be defined in the initial step of any LCA application. This is because it is believed that the model and the simulation assumptions will have an impact on the LCA output. By doing this, the likelihood of incorrectly interpreting LCA results is reduced [5]. Buildings on the other hand are unique and differ from controlled industrial processes comprehensively. **Figure 1** shows the steps that are crucial for the whole life cycle assessment of buildings. Due to factors such as buildings' long lifespans, different material uses globally, variable site-constrained construction techniques, the distinctive nature of each building, the evolution of function, maintenance, and retrofitting, etc., variability in the study of LCA is increased, and it is not easy to generalize even for a region. Because of that, many LCA studies have been constrained to specific objectives and limitations [7][8][9]. The second stage of any life cycle assessment is the development of a life cycle inventory (LCI), which is also a crucial step for the generalization of the process, and it includes resource flows as well as externalities that come with the product under assessment [5]. The third step is the evaluation of the potential environmental impact and risk associated with estimation using data from the LCI, which is also known as the Life Cycle Impact Assessment (LCIA).

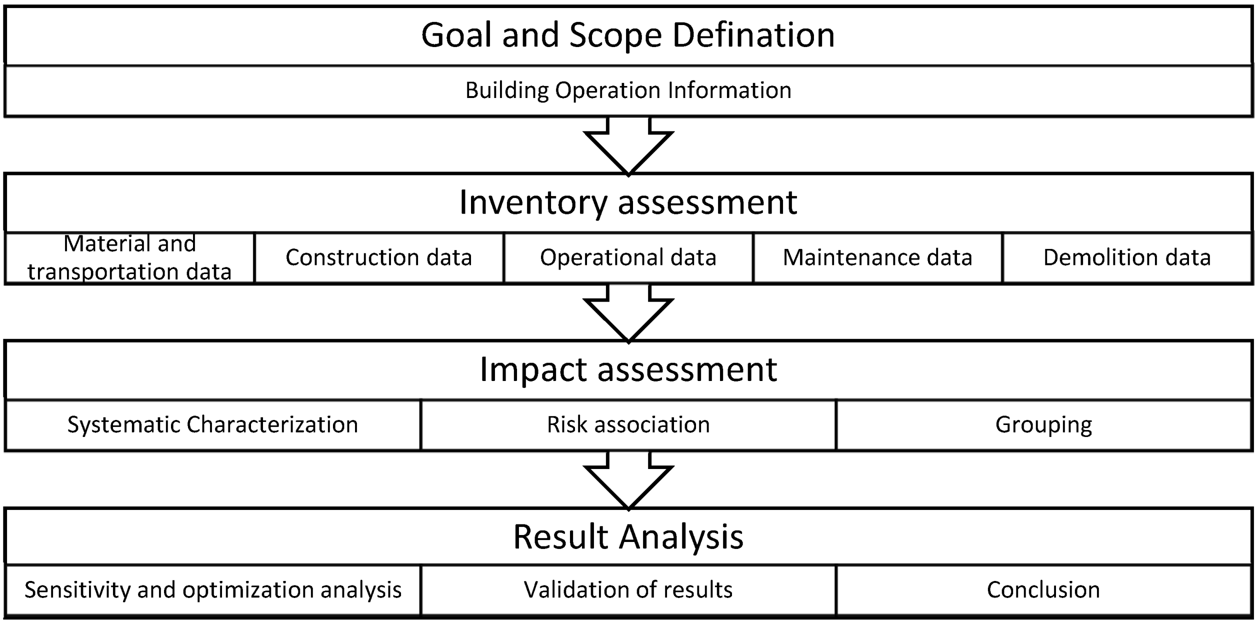

Figure 1. Critical steps in the life cycle assessment of buildings.

3. Introducing Early Environmental Assessment in the Design Process

Modern architectural practice is competent in examining the implications of new structures operationally, notably in the context of operational energy usage and carbon emissions. Embedded emissions design experience is still limited, despite social trends urging the incorporation of environmental considerations into the design process at the very beginning phases.

The design process is defined in both theoretical and experimental literature as a series of repetitive decision methods that gradually elevate the design to a superior complexity level while decreasing uncertainty. Beginning with the early conceptual phases, when many factors are ambiguous and the design team analyzes a wide variety of strategic and parametric possibilities, and concluding with the project's completion when the final building eliminates all uncertainty, the design changes with time. If environmental effects are to be successfully included in the early design phase, simpler methods that can deliver higher accuracy while using a few generic parameters are required.

- Generally, construction professionals utilize a simplified geometric model, which predicts the areas and quantities of building components based on restricted geometric input data. A model, which can calculate both the areas and consumption of building elements, might be used early in the design phase to estimate the influence of building form on embodied carbon. Through this method, a link between the geometric model's accuracy and its use time can be established;

- Rather than limiting the embodied carbon assessment of building elements to after the completion of a chosen building design, a more effective method would be to select suitable building elements from an inventory of a large number of predefined building elements with embodied carbon results at the early design stage. This method would have a greater impact.

A simple solution can be presented by integrating these two techniques, making embodied carbon data more available and usable for non-technical customers and construction professionals for the early design process with the development of low-embodied carbon buildings.

- Building Geometry Calculation: Based on minimal geometric input data, a simpler geometric building model is built, which calculates the area and quantity of construction elements.
- Building and Material Lifespan: As the building comprises different elements, and each element has a different lifespan within the life span of the whole building, it is necessary to set out a process that identifies both.
- Parametric Variation: The building elements that are predefined cover the diversity of design solutions for all internal and external elements, primarily related to the typological variations' specification; therefore, the first step is the selection of predefined building elements according to the requirements.
- Embodied Carbon Calculation: Every typological variation is subjected to the evaluation of embodied carbon throughout its life cycle. The data must be compiled into an inventory of pre-defined building elements and carbon data.
- Tool for Embodied Carbon Design: The design tool pairs geometric data with specified construction parts to quickly assess the embodied carbon of structures.
- Detailed Building LCA vs. Simplified: The results obtained from the simple tool are compared to those of a thorough building LCA, and the differences are addressed.

It is feasible to construct simpler embodied carbon tools, to save time, and this can also deliver enhanced assessment results such as the LCAP tool, which gives more precision in the early design process by utilizing fewer generic parameters [10]. For the secondary building parts and services, a similar approach must be followed, which is now not included in the model, and would assist the ongoing development of the tool. This would include calculating material consumption per square meter of floor space for doors, staircases, heating/ventilation systems, and other construction components. This would enable the tool to learn and expand with these elements, increasing the instrument's accuracy even further, enabling it to be utilized for later stages of the building's life cycle.

Generally, for the environmental performance of the product, two methodologies are established, life cycle assessment and carbon footprint; such is the case of building assessment. With the established methodologies, common quantitative claims of life cycle assessment exist in two forms, environmental product declaration (EPD) and product carbon footprint (CFP). For the lifecycle-based quantitative claims, it is necessary for the product to be open to the sources of data, the boundaries of the system, the recycled product's impacts and the choice of measurement [11]. In the building's life cycle assessment, two established methodologies play a vital role to achieve the lifecycle-based quantitative claims. As the building constitutes different materials and shows different maintenance requirements in different stages of its life cycle, the EPD and the advancement in the modeling options of the material sources and system boundaries according to region and requirement lead to a detailed life cycle assessment of the building in any stage. The EPD application in the early stage leads to the detailed analysis of CFP in any stage of the building's life cycle. However, for the EPD to support comparable EPDs, product category rules (PCRs) are considered mandatory to define specific rules for products serving the same function [12]. For the PCRs to develop, ISO 14,025 [13] presents the procedures and content required for a PCR, as well as requirements for comparability. However, standards present a defined set of rules and will not be sufficient for the development of PCRs for every requirement, which can also be called supplementary requirements. In the building sector, several documents and standards have been published other than ISO 14025, such as EN 15,804 [14], EN TR 15,941 [15], EN 15643-1 [16], and many more, which promise to serve the purpose of comparison and comparative assertion, but they also require a certain form of PCRs to carry out the promise. For this purpose, EN 15084 + A1 [14] is presented for the further development of EPDs [17]. With the contribution and collaboration of developers, PCRs are developed according to regions and requirements. Although such developments are the case in Europe or other developed nations, developing nations still fail to understand the concept of EPDs and PCRs.

4. Embodied Carbon in Different Stages of the Building Life Cycle

Construction, maintenance, and demolition trash have become a major source of solid waste for the environment and society in developing and developed countries, due to the tremendous rise of the construction sector globally in recent decades due to population increase; 20–60% of the world's solid waste stream is produced by the construction industry [18]. Construction-related garbage makes up roughly 20–30% of all solid waste produced in the European Union (EU), 30% in Canada, 29% in the United States, 26% in Hong Kong, and 30–40% in Australia. [19][20][21][22][23]. As a result, while construction contributes greatly to global progress and money, it also has a severe influence on the environment. Waste is sometimes disregarded because it is seen as negligible in comparison to waste generated during operations.

Landfilling and incineration are two typical waste disposal methods that have wreaked havoc on society, both economically and environmentally, by accumulating garbage and exacerbating the problem of global warming by emitting carbon dioxide (CO_2) during procedures [24][25].

Rapid population expansion has accelerated construction operations, resulting in increased trash output and embodied carbon across the phases of an existing building's lifetime. Demolition operations contribute the majority of the waste, whereas construction trash makes up the smallest portion of the entire waste portion. Despite the fact that the construction stage generates the least waste, it is possible to reduce the waste rapidly and effectively, with the option of better site management and improved information flow and coordination among members of the design team during the design and construction phases. Maintenance waste, on the other hand, has generally gone ignored among the three, despite having a higher potential of embodied carbon content than building waste—almost six times more over 50 years. The durability and quality of materials will dictate how often they must be maintained, replaced, or repaired. Design rethinking and embracing lifecycle thinking are thus critical steps toward reducing waste and maximizing possible recovery.

EOL waste output and related embodied carbon are by far the highest. Because of different sorts of obsolescence or other factors, the destruction of the EOL of the building is sometimes unavoidable. It is possible that the materials or components can be reused or refurbished during lifecycle management, and design-out-waste concepts are employed from the early design stage, preventing landfilling. Furthermore, well-designed and -maintained buildings can survive longer, preserving most of the embodied carbon contained in the construction.

If appropriately collected, handled, and recycled, the wastes created at different phases of a building's lifetime may be reused and become important resources for the construction industry. The waste can be considered a valuable resource for substituting raw materials and reducing embodied carbon and landfill waste. The role of transportation in embodied carbon's impacts on waste has been demonstrated. As a result, minor changes in travel lengths may cause the outcomes to worsen. As landfill sites are rapidly filling up and possible new sites for dumping waste are located further away from built-up regions, requiring a longer journey, this is becoming the case. The most essential technique to minimize the embodied carbon in the three stages of buildings is to avoid waste formation so that resources are not wasted, and the environment is not harmed. Addressing waste minimization through design optimization and early stakeholder involvement is key to the strategy's success.

References

1. Soust-Verdaguer, B.; Galeana, I.B.; Llatas, C.; Montes, M.; Hoxha, E.; Passer, A. How to conduct consistent environmental, economic, and social assessment during the building design process. A BIM-based Life Cycle Sustainability Assessment method. J. Build. Eng. 2021, 45, 103516.
2. Azis, A.A.A.; Memon, A.H.; Rahman, I.A.; Nagapan, S.; Latif, Q.B.A.I. Challenges faced by construction industry in accomplishing sustainablity goals. In Proceedings of the 2012 IEEE Symposium on Business, Engineering and Industrial Applications, Bandung, Indonesia, 23–26 September 2012; pp. 630–634.
3. Buildings and Climate Change Summary for Decision-Makers Sustainable Buildings & Climate Initiative. Available online: http://www.tge.ca (accessed on 21 July 2022).
4. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of buildings: An overview. Energy Build. 2010, 42, 1592–1600.
5. Pomponi, F.; Giesekam, J.; Hart, J.; Bernardino, D.A. Embodied Carbon: Status Quo and Suggested Roadmap. 2020. Available online: https://zerowastescotland.org.uk/sites/default/files/Embodied_carbon_spreads%20final.pdf (accessed on 31 October 2022).
6. International Organization for Standardization. Environmental Management: Life Cycle Assessment; Requirements and Guidelines; ISO: Geneva, Switzerland, 2006; Volume 14044.

7. Rashid, A.F.A.; Yusoff, S. A review of life cycle assessment method for building industry. Renew. Sustain. Energy Rev. 2015, 45, 244–248.

8. Dossche, C.; Boel, V.; De Corte, W. Use of Life Cycle Assessments in the Construction Sector: Critical Review. Procedia Eng. 2017, 171, 302–311.

9. Sharma, A.; Saxena, A.; Sethi, M.; Shree, V. Varun Life cycle assessment of buildings: A review. Renew. Sustain. Energy Rev. 2011, 15, 871–875.

10. Marsh, R.; Rasmussen, F.N.; Birgisdottir, H. Embodied Carbon Tools for Architects and Clients Early in the Design Process. In Embodied Carbon in Buildings: Measurement, Management, and Mitigation; Springer: Berlin/Heidelberg, Germany, 2018; pp. 167–190.

11. Subramanian, V.; Ingwersen, W.; Hensler, C.; Collie, H. Comparing product category rules from different programs: Learned outcomes towards global alignment. Int. J. Life Cycle Assess. 2012, 17, 892–903.

12. Fet, A.M.; Skaar, C. Eco-labeling, Product Category Rules and Certification Procedures Based on ISO 14025 Requirements. Int. J. Life Cycle Assess. 2006, 11, 49–54.

13. ISO 14025; Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures. International Organization for Standardization: Geneva, Switzerland, 2006.

14. EN 15804: 2012+ A1: 2013; Sustainability of Construction Works-Environmental Product Decla-Rations-Core Rules for the Product Category of Construction Products. Publications Office of the European Union Luxemburg: Luxemburg, 2013.

15. TR 15941; Sustainability of Construction Works. Environmental Product Declarations. Methodology for Selection and Use of Generic Data. BSI (British Standards Institution): London, UK, 2010.

16. EN 15643-1; Sustainability of Construction Works—Sustainability Assessment of Buildings—Part 1: General Framework. CEN: Brussels, Belgium, 2010.

17. Passer, A.; Lasvaux, S.; Allacker, K.; De Lathauwer, D.; Spirinckx, C.; Wittstock, B.; Kellenberger, D.; Gschösser, F.; Wall, J.; Wallbaum, H. Environmental product declarations entering the building sector: Critical reflections based on 5 to 10 years experience in different European countries. Int. J. Life Cycle Assess. 2015, 20, 1199–1212.

18. Crowther, P. Re-valuing construction materials and components through design for disassembly. In Unmaking Waste in Pro-duction and Consumption: Towards the Circular Economy; Emerald Publishing Limited: Bingley, UK, 2018.

19. Randell, P.; Pickin, J.; Reviewers, B.G.; Wardle, C. Waste Generation and Resource Recovery in Australia Final Report Pre-Pared for Department of Sustainability, Environment, Water, Population and Communities Waste Generation and Resource Recovery in Australia Reporting Period 2010/11 Final Report Version 2.6 P321 Blue Environment Prints on 100% Recycled Content Paper. 2010. Available online: www.blueenvironment.com.au (accessed on 31 October 2022).

20. Yuan, H.; Lu, W.; Hao, J.J. The evolution of construction waste sorting on-site. Renew. Sustain. Energy Rev. 2013, 20, 483–490.

21. Yeheyis, M.; Hewage, K.; Alam, M.S.; Eskicioglu, C.; Sadiq, R. An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. Clean Technol. Environ. Policy 2012, 15, 81–91.

22. Mália, M.; de Brito, J.; Pinheiro, M.D.; Bravo, M. Construction and demolition waste indicators. Waste Manag. Res. J. Sustain. Circ. Econ. 2013, 31, 241–255.

23. Arslan, H.; Cosgun, N.; Salg, B. Construction and Demolition Waste Management in Turkey. In Waste Management—An Integrated Vision; InTech: Vienna, Austria, 2012.

24. Marshall, R.E.; Farahbakhsh, K. Systems approaches to integrated solid waste management in developing countries. Waste Manag. 2013, 33, 988–1003.

25. Banias, G.; Achillas, C.; Vlachokostas, C.; Moussiopoulos, N.; Tarsenis, S. Assessing multiple criteria for the optimal location of a construction and demolition waste management facility. Build. Environ. 2010, 45, 2317–2326.