Case Study-Based Assessment of Carbon Footprint Reduction in Construction Materials Using BIM-Integrated LCA and Sensitivity Analysis

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Abstract

Achieving net-zero emissions is a fundamental goal for environmental sustainability and the transition to a circular economy. The construction and mining sectors contribute approximately one-third of global emissions, emphasizing the urgency of adopting effective mitigation strategies. Reducing the carbon footprint and CO_2 emissions in these industries is a critical challenge for promoting sustainable development and optimizing material usage. This study aims to quantify the carbon footprint of major building materials, specifically concrete, steel, and wood, assess potential CO_2 emission reductions, and evaluate their environmental impact. The research integrates Building Information Modeling (BIM), Life Cycle Assessment (LCA), and Sensitivity Analysis (SA) to establish environmental impact benchmarks. A case study approach was employed to analyse the carbon footprint of construction materials. The study utilized LCA to assess the embodied carbon at various life cycle stages (A1 to A3), identifying key contributors to global warming potential, acidification, eutrophication, and ozone depletion. Sensitivity analysis was conducted to evaluate the influence of material selection on overall emissions, while BIM integration facilitated a comprehensive visualization of the environmental impact. The analysis revealed that the embodied carbon from LCA stages A1 to A3 represents the primary contributor to environmental degradation. The study demonstrated a reduction in material-related carbon emissions from 662 kg CO_2e/m^2 to 506.8 kg CO_2e/m^2. Additionally, the global warming impact of building materials decreased from 10.57 kg CO_2e/m^2/year to 8.45 kg CO_2e/m^2/year. The results confirm that material type and quantity selected during the production stage significantly influence the overall embodied carbon. The findings of this study support sustainable decision-making in the construction industry by promoting material substitution strategies that replace high-emission components with low-carbon alternatives. The integration of BIM, LCA, and SA provides a robust framework for reducing environmental impact while fostering the reuse and recycling of construction materials. These insights contribute to advancing circular economy principles in the built environment. The above-mentioned analyses will be related to the possibilities of adapting the material mining heritage for new functions instead of constructing new buildings.

Keywords: *Carbon emission reduction; Life Cycle Assessment (LCA); Building Information Modeling (BIM); Circular economy; Sensitivity analysis*

1. Introduction

Global greenhouse gas (GHG) emissions reached an all-time high of 57.1 $GtCO_2e$ in 2023, representing a 1.3% increase (0.7 $GtCO_2e$) compared to the previous year, as reported in the Emissions Gap Report by UNEP [1]. According to the Global Status Report [2], CO_2 emissions from building operations and construction also peaked in 2022, accounting for approximately 37% of total global CO_2 emissions—nearly 10 $GtCO_2$—resulting from both building operations and the production of construction materials. The continual rise in CO_2 emissions, particularly from the construction sector, underscores the urgent need to implement effective mitigation strategies to prevent the irreversible consequences of climate change [3].

In line with international climate targets, the European Union (EU) has committed to reducing domestic GHG emissions by 90% by 2050 compared to 1990 levels [4]. A key pillar of the EU's "Europe 2020" energy strategy is the reduction of total energy consumption through energy efficiency improvements [3]. Lowering the carbon footprint in construction is therefore not only crucial for meeting these targets but also supports innovation and encourages sustainable practices among policymakers and stakeholders. However, global adoption of low-emission strategies is hindered by inconsistent methodological approaches used in life cycle emissions assessments [5].

Achieving net-zero emissions by 2050, as outlined in the 2015 Paris Agreement, requires a comprehensive evaluation of CO_2 emissions associated with construction and mining activities. A deeper understanding of the embodied carbon in construction materials is critical in this process. As highlighted by Ostręga et al. [6], the construction industry plays a central role in both resource consumption and GHG emissions, positioning it as a key sector for climate action and sustainable resource management.

The adoption of circular economy principles offers promising opportunities for emission reduction in the construction sector. It promotes resource efficiency, use of renewable materials, and adaptive reuse of existing structures. As noted by Pikoń et al. [7], circular construction enables the design of buildings that are energy-efficient, recyclable, and adaptable to changing functional needs. Globally, the construction industry is responsible for consuming around 40% of all extracted raw materials [8], further emphasizing the need for a systemic transition.

The role of embodied energy in the life cycle of buildings has become increasingly prominent. Hu [9] reports that, for a typical single-family house, embodied energy can represent up to 40–50% of the total primary energy use over its life cycle. This highlights the importance of accurately quantifying carbon emissions across the entire building life cycle, from material extraction to end-of-life phases [10].

Life Cycle Assessment (LCA) is an established method for evaluating the environmental impacts of buildings, including stages such as manufacturing, construction, operation, and demolition ("cradle-to-grave") [11]. When combined with Building Information Modeling (BIM), LCA enables automatic extraction and assessment of building materials and their environmental impacts [12]. BIM models enriched with LCA-related data (e.g., environmental impact categories) allow for rapid assessment of embodied carbon—defined as the GHG emissions associated with material production, transportation, construction, and disposal [13].

Over the last decade, commercial tools integrating BIM and LCA, such as One-Click LCA, have been developed to assess embodied environmental impacts efficiently. However, current tools generally lack the capacity to fully account for operational emissions incurred during a building's use phase [12].

In addition, sensitivity analysis (SA) has proven valuable in identifying key variables influencing LCA outcomes and guiding targeted data collection. SA differs from uncertainty analysis (UA), which propagates data uncertainties throughout the model to assess the overall uncertainty of results [14]. substituting high-emission components with lower-carbon alternatives, while promoting the reuse and recycling of extant materials alongside the adaptive reuse of current building materials.

The article focuses on evaluating the environmental impact of construction materials through a comprehensive life cycle assessment (LCA) integrated with sensitivity analysis (SA). It seeks to quantify the carbon footprint of key materials—namely concrete, steel, and wood—while identifying critical life cycle stages that contribute most significantly to overall emissions. By leveraging Building Information Modeling (BIM) to support LCA, the research also explores the potential of digital tools to enhance material selection and carbon mitigation strategies. Emphasis is placed on strategies that promote circular economy principles, such as material reuse, recycling, and adaptive design. The anticipated findings are expected to demonstrate that substituting high-emission materials like concrete with timber-based alternatives can lead to substantial reductions in embodied carbon. Ultimately, the study aims to inform sustainable decision-making in the construction and mining sectors by providing actionable insights into low-carbon material choices and integrated environmental assessment methods.

2. Carbon emissions in the construction and mining industry

2.1 Background and Terminology

The term embodied carbon refers to the total lifecycle greenhouse gas (GHG) emissions—expressed in carbon dioxide equivalents (CO_2e)—that occur during the extraction, processing, manufacturing, and transportation of construction materials, as well as during the construction and end-of-life phases of a building [26],[28]. In recent years, the term embodied carbon has often been used interchangeably with carbon footprint when discussing the environmental impacts of building materials. Embodied carbon assessments typically form a subset of life cycle analysis (LCA), focusing exclusively on GHG emissions as the impact category [15].

The embodied carbon of construction materials is commonly assessed in stages A1 to A3 of the LCA framework, which include raw material extraction (e.g., quarrying or mining), manufacturing, and transportation to the factory gate. Overall, the carbon life cycle of a building is divided into two major components: embodied carbon and operational carbon [3]. Previous research indicates that approximately 6.13 billion square meters of buildings are constructed globally each year, resulting in roughly 3,729 million metric tons of embodied carbon emissions associated with new construction [16].

As shown in Figure 1, building operations account for 28% of total global CO_2 emissions, followed by transportation (23%) and the production of concrete, aluminium, and steel (23%).

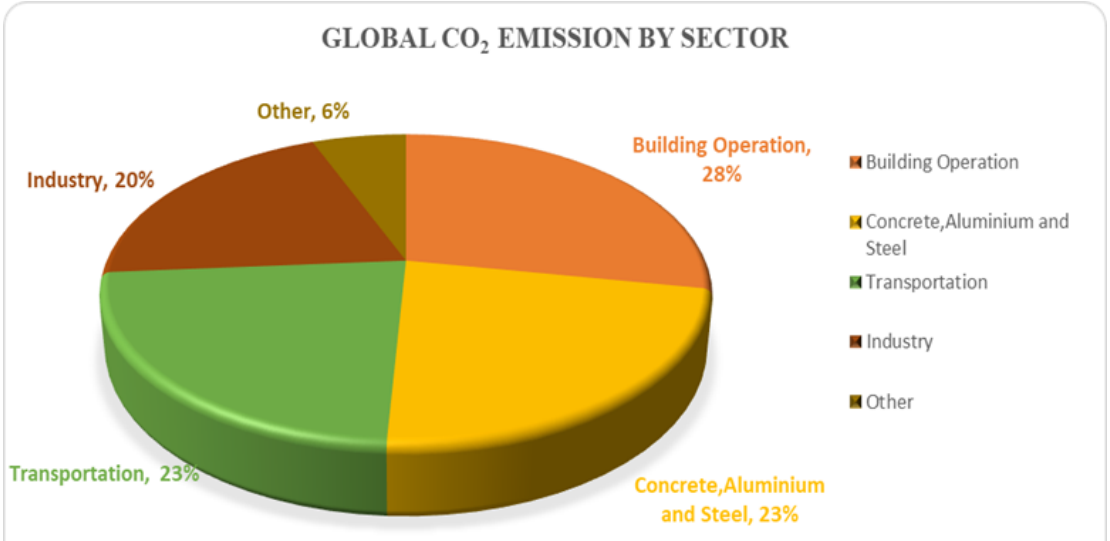

Fig. 1. Global CO_2 emissions by sector. Source: International Energy Agency, as cited in Global Status Report (Adapted from [27])

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardized method used to evaluate the environmental impacts associated with all stages of a product's life. In the context of construction, it provides a comprehensive assessment of greenhouse gas (GHG) emissions resulting from raw material extraction, transportation, manufacturing, construction, use, maintenance, and end-of-life processes [17], [29]. LCA is particularly useful for quantifying the carbon footprint of materials used in new construction and refurbishment projects. Tools such as One-Click LCA are commonly employed to streamline this evaluation process.

LCA is increasingly integrated into the design and decision-making phases of construction projects to support the reduction of environmental impacts [3]. The results of an LCA represent a broad environmental profile of a building, encompassing indicators such as energy use, global warming potential, habitat disruption, resource depletion, and toxic emissions. In the construction sector, process-based LCA methods are most commonly applied [18].

The scope of LCA can be categorized into four main approaches:

- Cradle to Grave: Covers the full life cycle of a product, from raw material extraction through manufacturing, use, and final disposal.
- Cradle to Gate: Encompasses processes from raw material extraction to the factory gate, excluding the use and end-of-life stages.
- Gate to Gate: Focuses on a single phase within the product lifecycle, typically a specific production or manufacturing stage.
- Cradle to Cradle: Includes raw material extraction, use, and recycling processes, aligning with circular economy principles.

According to ISO 14044:2006 and guidance from the British Standards Institution (BSI), a complete LCA is divided into four life cycle stages:

- Production (A1–A3): Raw material supply, transport, and manufacturing
- Construction (A4–A5): Material transport to site and installation
- Use (B1–B7): Building operation, maintenance, and repair
- End-of-Life (C1–C4): Deconstruction, waste processing, and disposal

Production Stage (A1-A3)

The production stage represents the embodied carbon emissions associated with the extraction of raw materials, their transportation, and manufacturing processes, commonly referred to as *cradle-to-grave*. Embodied carbon at this stage is calculated using the formula:

$EC_{A1-3} = \Sigma^{n}_{i\text{-}th} (EC_{prod} \times ECC_i)$
$EC_{A1\,-\,A3}$: Embodied carbon from stages A1 to A3 and
EC_{prod} Mass or quantity of the i-th material (kg)
ECC_i means Embodied Carbon co-efficient for the i-th material (kg CO_2e/kg),

Transportation Stage (A4)

Stage A4 accounts for the environmental impact of transporting materials from the manufacturing facility to the construction site—this is often referred to as gate-to-site. The embodied carbon in this stage is calculated by multiplying the mass of each component (including waste, if applicable) by the transportation distance and an emission factor corresponding to the mode of transport:

$EC_{transport} = \Sigma^{n}$ (Massi x $ECC_{transport,i}$), Where: $EC_{transport\ _}$ Embodied carbon during transportation (Kg CO_2e)

$ECC_{transport,i}$: Embodied carbon factor for the transportation per unit distance (KgCO_2e/Kg.km)

This phase is critical for materials sourced internationally or transported over long distances, as the carbon impact may be substantial [19].

Use Stage (B1–B7)

The use stage encompasses the operational phase of the building, including emissions associated with its performance, maintenance, repair, and eventual refurbishment. Although not always included in embodied carbon calculations, this phase represents operational carbon—the GHG emissions generated through energy and resource consumption during the building's service life. It includes:

- B1: Direct use-phase emissions (e.g., emissions from leaks, off-gassing)
- B2: Maintenance (e.g., cleaning, minor replacements)
- B3: Repair (e.g., fixing damaged components)
- B4: Replacement of building components or systems
- B5: Refurbishment (e.g., modernization or major renovation)
- B6: Operational energy use (heating, cooling, lighting, ventilation)
- B7: Operational water use (water treatment and pumping)

Operational energy use (B6) typically accounts for the largest share of GHG emissions in conventional buildings. However, with improvements in energy efficiency and the use of renewable sources, embodied carbon is becoming increasingly significant in total life cycle emissions.

End-of-Life Stage (C1–C4)

This phase captures the environmental impacts associated with the deconstruction, transport, processing, and disposal of building materials at the end of their service life. It includes:

- C1: Deconstruction or demolition activities
- C2: Transportation of waste materials to processing or disposal facilities
- C3: Waste processing for reuse, recovery, or recycling
- C4: Final disposal (e.g., landfilling or incineration without energy recovery)

The end-of-life stage is essential in understanding the full environmental cost of a building, especially for materials that cannot be reused or recycled. Accurate modelling of this phase is also crucial in cradle-to-cradle and circular economy approaches.

To article, the analysis will focus primarily on the embodied carbon stages of the building life cycle, specifically modules A1–A5, which include material production, transportation, and construction processes. While stages B1–B7 (use phase) and C1–C4 (end-of-life phase) are integral components of a complete life cycle assessment, they will not be examined in detail in the following sections. This exclusion is intended to narrow the scope of the research and concentrate on the phases that contribute most significantly to initial carbon emissions and material-related environmental impacts.

2.3 Carbon Emission Factor

According to the Intergovernmental Panel on Climate Change (IPCC), the carbon emission coefficient represents the amount of carbon dioxide emitted per unit of energy consumed, typically through combustion or material usage. Building upon this concept, the carbon emission factor extends the idea by incorporating emissions related to specific materials and their associated processes, particularly transportation. This approach, known as the carbon emission coefficient method, has been further refined by Luo et al. [20]. A summary of carbon emission factors for selected construction materials, considering average transportation distances, is presented in Table 1. These data provide essential inputs for life cycle carbon assessments, enabling accurate estimation of embodied emissions across different material categories.

Tab. 1: Carbon emission factors and transportation distance of main building materials.

Construction materials	Carbon emission factor	Mean transportation distance/km	Building materials category	Carbon emission factor	Transportation Distance/km
Steel (large)	2.80kgCO_2/kg	60	Sand	3.49kgCO_2e/m^3	40
Steel (Small and medium	2.19kgCO_2/kg	60	Copper conductor cable	9.41kgCO_2e/kg	70
Steel (wire)	2.2kgCO_2/kg	60	PVC pipe	9.74 kgCO_2e/kg	25
Rebar	2.31kgCO_2/kg	60	Polystyrene Extruded plate	669kgCO_2e/m^3	25
Cement	0.977kgCO_2e/m^2	25	Architectural potteries	19.5kgCO_2e/m^2	40
Concrete C30	297kgCO_2e/m^2	15	Windows (Aluminium)	46.3kgCO_2e/m^2	55
Concrete C40	326kgCO_2e/m^2	15	Water paints	6.55 kgCO_2e/kg	50
Clay brick	349kgCO_2e/per 1000 block	25	Wood	139kgCO_2e/m^3	35
Hollow clay brick	290kgCO_2e/per 1000 block	25	Waterproof coil (SBS)	2.38kgCO_2e/m^2	25
Common Concrete Block	171kgCO_2e/m^2	25	Stone	3.17kgCO_2e/t	40
Fly ash aerated Concrete block	327kgCO_2e/m^2	25			

2.4 Environmental Product Declaration (EPD)

Environmental Product Declarations (EPDs) provide standardized, third-party verified documentation that communicates the environmental performance of a product based on a Life Cycle Assessment (LCA). In the construction industry, EPDs play a crucial role in promoting carbon emission reductions by enabling the comparison of materials and products across consistent environmental indicators, thus supporting informed decision-making and the selection of more sustainable options.

An EPD discloses key information about a product's environmental impacts throughout its life cycle, from raw material extraction, manufacturing, and use to end-of-life. These declarations are typically valid for five years and must conform to

internationally recognized standards such as ISO 14040/14044 [21], EN 15804 [22], and ISO 21930 [23].

In the context of green building certification, EPDs contribute toward gaining LCA-related credits in schemes such as LEED, BREEAM, and others. They support transparency and facilitate sustainability assessments by providing quantitative data on environmental categories including global warming potential (GWP), ozone depletion, acidification, eutrophication, and resource use.

EPDs are increasingly regarded as essential tools in evaluating and comparing the carbon footprint of building materials. Software platforms such as One Click LCA® help automate the generation and analysis of EPDs, making them a practical benchmark in sustainable construction. A valid EPD allows all stakeholders, architects, engineers, developers, and certifiers, to access consistent and internationally accepted information on product sustainability.

By offering insights into a material's environmental profile and technical characteristics, EPDs form the basis for a Whole Building Life Cycle Assessment (WBLCA). This makes them indispensable for assessing sustainability potential and reducing the environmental impact of construction materials at both the component and building levels [24].

3. Method and Materials

3.1 Project Case Study

The case study investigates the embodied carbon and greenhouse gas (GHG) emissions associated with a two-storey building, with the objective of demonstrating how material selection and modelling techniques can support the reduction of environmental impact in alignment with the IPCC's net-zero emission goals. The case study applies an integrated Building Information Modeling (BIM) and Life Cycle Assessment (LCA) approach, using a 3D model and Industry Foundation Classes (IFC) data exchange supported by the One Click LCA plugin, developed by Bionova Ltd.

The building comprises cast in-situ reinforced concrete pile foundations and floor slabs constructed from concrete and glue-laminated timber (glulam). While the columns and beams are primarily made of cast-in-place concrete, the first-floor columns are constructed using glulam to minimize embodied emissions. Roof trusses are predominantly composed of steel members, whereas floor and wall systems feature prefabricated wood-based sandwich elements manufactured by Lättelement (Sweden).

The environmental impact analysis focuses on three major construction materials: concrete, steel, and wood, with attention to their respective quantities and structural roles. Concrete elements under analysis include pile foundations, slabs, columns, and beams. Steel accounts for approximately 10% of the roof system and 20% of the column structure. Wooden elements, including floor systems, 80% of roof trusses, and selected columns, were incorporated to enhance material circularity and reduce carbon footprint.

The assessment process follows a structured LCA flow, as illustrated in Figure 2, beginning with material take-off from the BIM model, followed by generation of Environmental Product Declarations (EPDs), parameter input, and result interpretation using One Click LCA software. The modelling output enables precise quantification of embodied carbon across structural systems and helps identify emission reduction opportunities.

Figure 3a shows the architectural plan of the case study building, while Figure 3b presents a 3D BIM model. Figure 3c depicts the internal structural arrangement used for the material take-off and carbon accounting of substructure and superstructure elements.

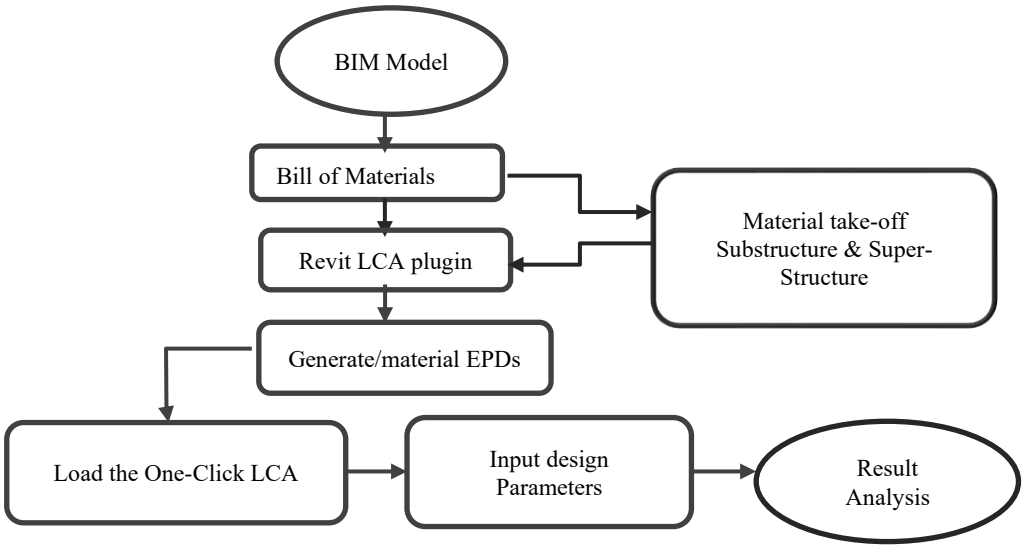

Fig. 2. Carbon Footprint analysis flowchart of BIM-LCA integration

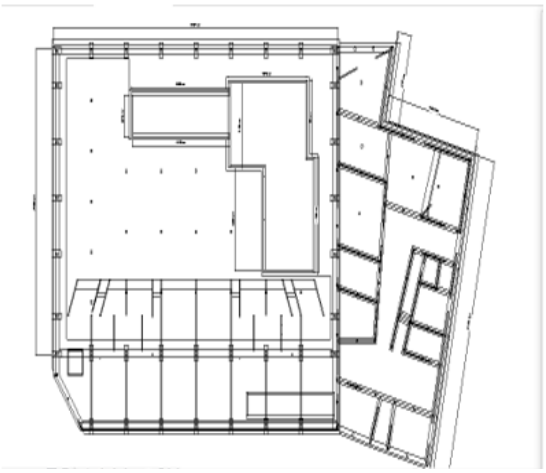

Fig. 3a. Architectural plan view of the case study building.

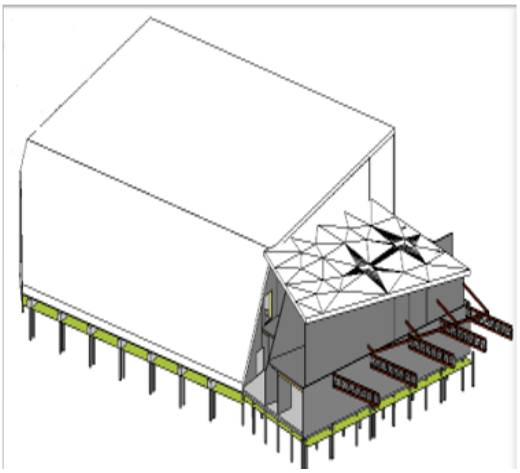

Fig. 3b. 3D external perspective of the case study building showing structural outline.

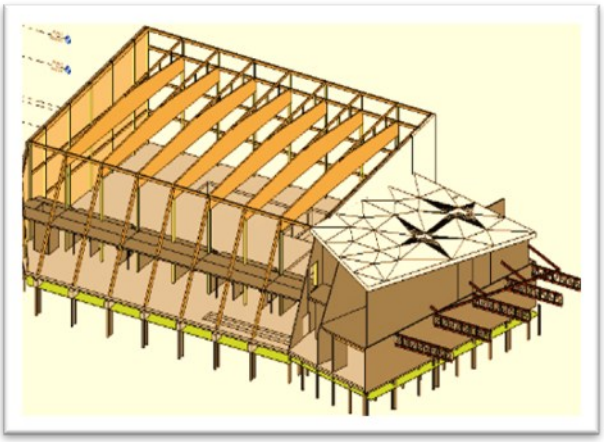

Fig. 3c. Internal structural view showing substructure and superstructure material allocation for LCA-based quantity take-off.

3.2 Data Collection and Calculation Assumptions

Building Information Modeling (BIM) was employed to facilitate the collection, organization, and analysis of building data relevant to the carbon footprint assessment. The model was developed and exported in IFC (Industry Foundation Classes) format and subsequently imported into Autodesk Revit software to enable material quantification and integration with the One Click LCA environmental assessment tool.

Quantities of selected construction materials—specifically concrete, steel, and wood—were extracted from the model's Bill of Quantities (BoQ). These quantities served as input parameters for calculating the embodied carbon of each material, using appropriate carbon emission factors derived from Environmental Product Declarations (EPDs) and referenced literature sources. This data-driven approach ensured consistency in evaluating material contributions to the overall carbon footprint across different life cycle stages.

3.3 Case study parameters

The primary data used in this study were obtained from SWECO, a multinational engineering consultancy firm. The case study building is a municipal sports complex located in Trosa, Sweden, designed and constructed by SWECO. A detailed 3D model of the building was created using Autodesk Revit, and the assessment of carbon emissions and environmental impacts was performed using the One Click LCA software developed by Bionova Ltd.

For the purposes of carbon footprint analysis, benchmarking, and environmental impact assessment, the following assumptions and boundary conditions were applied within the One Click LCA platform:

- Material product life: Defined by the *technical service life* of each product category.
- Material origin/localization: Assumed to be Poland for all construction materials.
- Building service life: Set to 60 years.
- LCA scope: Included modules A1–A3 (product stage), A4–A5 (construction stage), and B6 (operational energy use).
    - Due to the lack of actual operational data, B6 emissions were assumed and not modelled dynamically.
    - Life cycle stages B1–B5, B7, and C1–C4 (use and end-of-life phases) were excluded from this analysis but may be addressed in future work.

- Environmental Product Declarations (EPDs): Based on manufacturer-specific data when available or generic EPDs provided by the One Click LCA database.
- Operational energy consumption: Estimated based on assumptions rather than measured data due to the early design stage of the building.

This framework ensures a focused evaluation of embodied carbon associated with construction materials and processes, enabling comparative analysis and sensitivity testing of material substitution strategies.

4. Result and Discussion

4.1 Material Classification

To enable a detailed and systematic assessment of carbon emissions, the major structural components of the case study building were categorized into functional subgroups. This classification supports a comprehensive analysis of the embodied carbon footprint and the potential for emission reductions across key construction systems. Material quantities were extracted using Building Information Modeling (BIM) tools, specifically Autodesk Revit, through automated material take-off processes. Each building element was assigned to a specific subgroup based on its structural function and material type. The areas (in m^2) and volumes (in m^3) were calculated directly from the BIM model, providing a reliable and consistent dataset for carbon footprint analysis (Table 2).

Tab. 2. Classification of major building Elements

Building Elements	**Sub-group Elements**	**Area (m^2)**	**Volume used (m^3)**
Foundation	Pile foundation (Precast)	546.126	30.911
	Isolate foundation (in-situ)	167.457	28.852
Super-structure	Floor	7771.987	721.353
	Wall (Wood)		557.198
	Column & Beam (Concrete elements)	282.062	5.543
	Column & Beam (Steel elements)	245.723	1.159
	Column & Beam (Glulam)	1582.100	123.280
Roof	Steel & wood	8166.67	1291.715

The classification forms the basis for the carbon footprint calculation in subsequent sections. It enables comparison of embodied carbon intensities across different material types (concrete, steel, and wood) and structural zones (foundation, superstructure, and roof).

4.2 Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the influence of material selection and sourcing on the building's overall carbon footprint. This analysis aimed to simulate the effects of varying key parameters, such as material type, carbon content, and geographic origin, on embodied carbon emissions and their environmental impact. By altering input assumptions and carbon coefficients for major materials, the study explored how design decisions can contribute to or mitigate greenhouse gas emissions.

Two scenarios were modelled and analysed using the One Click LCA platform:

- Scenario 1 – Material Substitution (Decarbonisation) - High-carbon-intensity materials in the baseline design were substituted with lower-carbon alternatives using Environmental Product Declarations (EPDs) to guide material replacement. This scenario demonstrates how thoughtful selection of materials can contribute to significant carbon reductions (Table 3).
- Scenario 2 – Material Localization Impact - This scenario assessed the effect of geographic location on carbon emissions by comparing carbon benchmarks for Poland, Sweden, and the United Kingdom. The aim was to determine how material sourcing and transportation distances influence total embodied emissions.

Tab. 3. Scenario 1 – Material Substitution for Decarbonisation

Building Element	**Baseline Material**	**Substitute Materials (Low Carbon)**
Wall	Glulam (Lättelement)	CLT (Low carbon)
Roof	Glulam & Steel Lättelement	Glulam (Low carbon)
Floor	In-situ Conc.	CLT floor
Structural frame	Steel & Glulam	Steel and CLT
Pile foundation	Concrete cast in Place	Concrete Precast

This analysis highlights the potential for decarbonisation through material substitution and encourages the adoption of low-

emission construction systems, particularly in the early design phase. Scenario 2 results (carbon by location) are presented and discussed in Section 5.

4.3 Building Materials Carbon Footprint (BMCF) Findings

The greenhouse gas (GHG) emissions associated with individual building materials were assessed across different life cycle stages in accordance with the LCA framework. The evaluation focused primarily on stages A1–A5, B6, and C1–C4, while stages B1–B5 and B7 were excluded due to insufficient data. For stage B6 (operational energy use), an assumed electricity consumption of 500 kWh was applied to reflect average usage during the construction stage.

As presented in Figure 4, the environmental impacts were analyzed based on multiple categories, including:

- Global warming potential (kg CO_2e)
- Acidification potential (kg SO_2e)
- Eutrophication potential (kg PO_4e)
- Ozone depletion potential (kg CFC-11e)
- Formation of ozone in the lower atmosphere (kg Ethene equivalents)

The results indicate that the production stage (A1–A3) is the most carbon-intensive, contributing:

- 88.38% of total CO_2e emissions,
- 94.39% of SO_2e (acidification),
- 98.34% of PO_4e (eutrophication), and
- 99.24% of CFC-11e (ozone depletion).

These findings highlight the dominant role of material manufacturing and processing in the overall environmental footprint of the building. Conversely, the transportation stage (A4), installation stage (A5), and deconstruction stage (C1–C4) contributed relatively minor shares to the total impact, ranging from 0.1% to 8%, depending on the impact category.

The quantified results of these assessments are summarized in Table 4, where the total global warming potential was calculated at 829,779.36 kg CO_2e, corresponding to 634.27 kg CO_2e/m^2 based on a gross internal floor area of 1308.25 m^2. Similarly, emissions per square meter were found to be:

- 3.11 kg SO_2e/m^2 (acidification),
- 2.17 kg PO_4e/m^2 (eutrophication),
- 1.24 kg Ethene/m^2 (ozone formation).

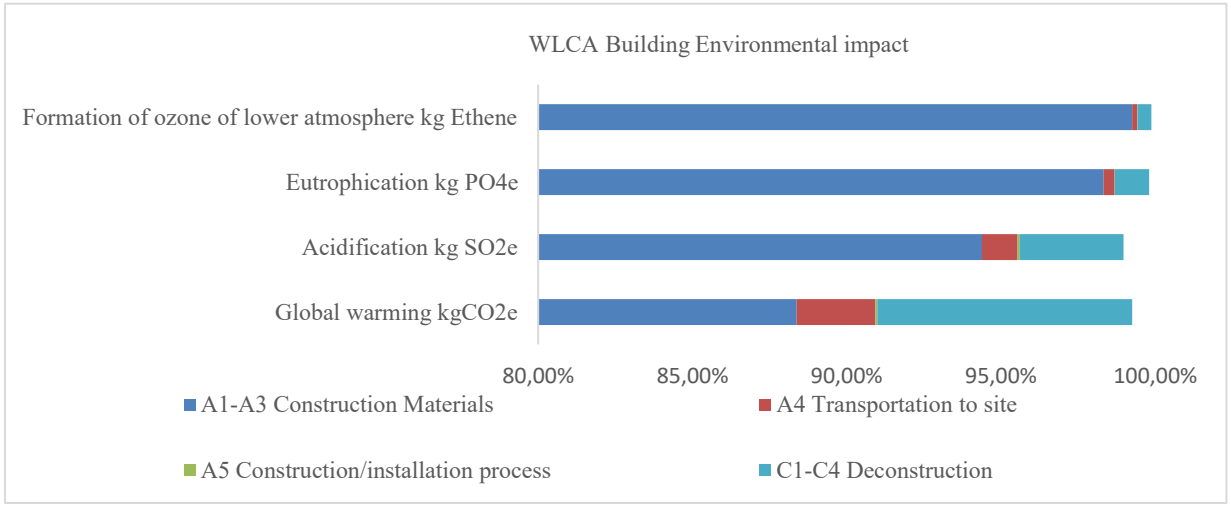

Fig. 3. Life Cycle Stages Environmental Impacts: Visualization of GHG emissions across A1–C4 stages by impact category

The effect of ozone depletion was found to be negligible across all stages. These results confirm the significance of conducting whole-building LCA (WB-LCA) in assessing environmental performance and identifying high-impact construction phases, particularly when considering carbon-intensive materials.

Tab. 4. Life Cycle Stages Environmental Impacts Summary: Numerical values of CO_2e, SO_2e, PO_4e, and other environmental metrics for each life cycle stage

Stages	Result category	Global warming kg CO_2e	Acidification kg SO_2e	Eutrophication kg PO_4e	Ozone depletion potential kg $CFC_{11}e$	Formation of ozone of lower atmosphere kg Ethene
A1-A3	Construction Materials	733,358.67	3844.01	2,796.04	0.01	1,606.02
A4	Transportation to site	21,207.97	47.02	9.92	0	2.7
A5	Construction/installation process	472.58	3.19	0.42	0	0.15
B6	Energy use	6,175.19	41.8	5.49	0	1.95
C1-C4	Deconstruction	68,564.95	136.66	31.44	0	7.21
D	External impacts (not included in totals)	−401,139.97	−998.73	−122.73	−0	−79.58
	Total	829,779.36	4,072.69	2,843.32	0.02	1,618.02
	Results per denominator					
	Gross Internal Floor Area (IPMS/RICS) 1308.25 m^2	634.27 kg CO_2e/m^2	3.11 kg SO_2e/m^2	2.17 kg PO_4e/m^2	0	1.24 kg O_3e/m^2

4.4 Embodied Carbon Heroes Benchmark

The Embodied Carbon Heroes Benchmark represents a standardized classification system used to evaluate the carbon intensity of buildings based on their life cycle emissions. In this study, the benchmark was employed to set performance targets for reducing embodied carbon and to compare outcomes across different design and material configurations. All simulations were conducted using the One Click LCA software, with a building lifespan of 60 years assumed for all materials.

The embodied carbon results were assessed for different regional contexts, including Poland, Eastern Europe, and the United Kingdom, to evaluate the influence of local energy grids, material sourcing, and transport distances on emission performance.

In the baseline scenario, the building's embodied carbon was calculated at 830 tons CO_2e, corresponding to 10.57 kg CO_2e/m^2/year or 629 kg CO_2e/m^2 over the full-service life. As shown in Figure 4a, this value falls into Class D on the Carbon Heroes Benchmark scale, which ranges from Class A (≤250 kg CO_2e/m^2) to Class G (≥900 kg CO_2e/m^2).

Following the material substitution strategies described in Section 4.3—specifically the replacement of high-carbon materials such as in-situ concrete and steel with low-carbon alternatives like CLT panels and glulam—a significant reduction in embodied carbon was achieved. The total carbon emissions decreased to 663 tons CO_2e, equivalent to 8.45 kg CO_2e/m^2/year or 501 kg CO_2e/m^2, improving the building's classification to Class C in the benchmark scale (Figure 4b).

These results demonstrate the effectiveness of low-carbon design interventions and underscore the importance of material optimization in achieving carbon reduction goals aligned with the Paris Agreement and IPCC net-zero pathways.

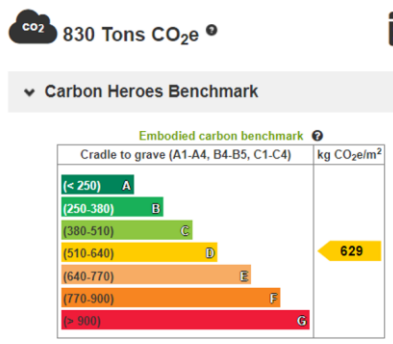

Fig. 4a, Embodied carbon benchmark for baseline building design (629 kg CO_2e/m^2 – Class D).

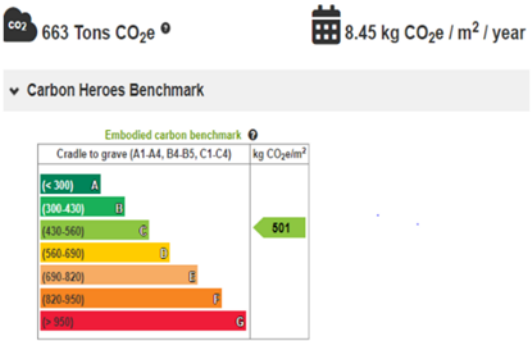

Fig. 4b. Embodied carbon benchmark after material substitution (501 kg CO_2e/m^2 – Class C).

5. Results and Discussion

This section presents the outcomes of the carbon footprint evaluation and sensitivity analysis performed on the selected building elements using the One Click LCA tool. The results compare the environmental impact of the baseline model with two alternative design scenarios aimed at reducing embodied carbon through material substitution and localization strategy.

The baseline building design, which incorporates conventional construction materials such as cast-in-place concrete, steel, and glulam wood, results in a total embodied carbon footprint of approximately 629 kg CO_2e/m^2. The largest contributors to embodied emissions were:

- Concrete foundations and slabs (including pile caps and structural floors)
- Steel roof members and structural frames

- Timber-based wall and column systems

The results indicate that concrete and steel dominate the emission profile, particularly in the A1–A3 stages (material production), with additional contributions from transportation (A4) and installation processes (A5).

Scenario 1 involved substituting high-carbon materials with lower-carbon alternatives based on available EPD data. Notable material changes included replacing:

- In-situ concrete slabs with cross-laminated timber (CLT)
- Steel-glulam roof structures with glulam-only systems
- Cast-in-place concrete foundations with precast concrete elements

These changes resulted in a reduction of approximately 80% in the total embodied carbon compared to the baseline. The most significant improvement was observed in the floor system, where CLT replacement reduced emissions by over 501 kg CO_2e/m^2.

The substitution of precast instead of in-situ concrete also contributed to reductions due to lower transportation energy, improved manufacturing efficiency, and reduced on-site waste.

In Scenario 2, the impact of material localization was assessed by comparing emission benchmarks from three countries: Poland, Sweden, and the United Kingdom. The analysis showed clear variation in embodied carbon values depending on:

- Transportation distances and infrastructure efficiency
- Local energy mix used in material production (e.g., Sweden's low-emission grid vs. Poland's coal-based grid)
- Regional manufacturing standards and efficiencies

The Swedish benchmark resulted in the lowest overall carbon footprint, while Polish benchmarks showed higher emissions due to higher carbon intensity in both manufacturing and transportation stages. Differences of up to 128 kg CO_2e/m^2 were observed across scenarios for the same materials, underscoring the importance of local context in sustainable material sourcing.

The results demonstrate that embodied carbon can be significantly reduced through early-stage design interventions, including material selection and sourcing strategies:

- CLT and glulam are highly effective in reducing emissions compared to concrete and steel, particularly in superstructure applications.
- Precast concrete offers measurable improvements overcast-in-place alternatives.
- Localization of material production and shorter transportation distances can further minimize carbon impact, especially when paired with cleaner national energy grids.

6. Summary

This study has demonstrated that the extraction, processing, and manufacturing of construction materials (LCA stages A1–A3) are the dominant contributors to the environmental impacts of buildings, particularly in terms of global warming potential and ozone layer depletion. The findings confirm that the embodied carbon of materials is strongly influenced by material type, production method, and sourcing location. These results are consistent with previous research [25], highlighting the potential of adaptive material reuse and circular economy practices in reducing environmental burdens.

By integrating Building Information Modeling (BIM) with Life Cycle Assessment (LCA) and sensitivity analysis, the study enabled a detailed and data-driven evaluation of carbon emissions. Scenario analyses showed that replacing high-carbon materials (e.g., conventional concrete and steel) with low-carbon alternatives (e.g., CLT and glulam) can substantially reduce embodied emissions, improving carbon performance benchmarks by up to 16%.

The application of One Click LCA and environmental product declarations (EPDs) supported the identification of effective decarbonization strategies. The study also emphasizes the importance of evaluating carbon impacts during early design stages, which empowers architects and engineers to make informed decisions on material efficiency, renewability, and reuse potential.

In addition, the research recommends:

- Prioritizing locally sourced materials to reduce transportation-related emissions.
- Favoring low-embodied carbon solutions such as engineered timber systems over traditional materials.
- Expanding future research to include currently excluded life cycle stages (B1–B5, B7, and C1–C4), which can further enrich environmental performance assessments.
- Investigating social and environmental benefits of retrofitting and reusing existing structures as a pathway to achieving net-zero construction goals.
- Ultimately, the study reinforces the role of BIM-integrated LCA tools in supporting the transition to sustainable construction and provides actionable insights for designers, policymakers, and stakeholders seeking to minimize the carbon footprint of the built environment.

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